Institute of Hydrology

Scientific Report 1997-98

Centre for Ecology & Hydrology
Natural Environment Research Council

The IH mission

We seek to advance and apply hydrological science to improve the management and sustainable use of fresh water for a better environment and an improved quality of life

Priority is given to:

- research leading to increased understanding of the hydrological cycle and of its component physical, chemical and biological processes,
- experimentation, monitoring and modelling to investigate variability and change in freshwater systems to reveal and predict the impact of human activities,
- securing relevant data to further such research and provide a sound basis for advice in the broad area of water affairs and public services

Scientific Report of the Institute of Hydrology 1997/98

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Foreword

The environmental agenda has shown no diminution during the year. Issues such as deforestation, dryland degradation and climate change persist. Natural disasters, resulting from flood and drought, have caused disruption to the lives of millions of people and many deaths worldwide. Man-made disasters, resulting from pollution or other causes, are all too evident.

Internationally, there is a growing political will to address such problems. The Commission on Sustainable Development (CSD) addressed the major theme of Freshwater during 1998. CSD reaffirmed that water resources are essential for satisfying basic human needs, health and food production, energy, the restoration and maintenance of ecosystems, and for social and economic development in general. The Right Honourable Michael Meacher, MP, Minister for the Environment, in presenting the 1998 NERC Lecture, showed both his personal and the Government's commitment towards sustainable management.

To address such issues a multi-disciplinary approach is needed and CEH, with one of the strongest capabilities in the world for undertaking holistic research in the terrestrial and freshwater sciences, is well placed in this respect.

The NERC Council places a high value on our science and has shown a willingness to invest in the future of CEH through a programme of rationalisation and restructuring. The first step has been to approve a £2.86 million extension to CEH's Wallingford site. I am confident that investments at other CEH sites, rising from the restructuring package approved by Council last year, will be made during the coming years.

The impact of the rationalisation and restructuring activity has understandably caused some uncertainty amongst staff during the year. However, despite this, staff remain highly skilled, innovative and well motivated, and it is to their credit that, during these uncertain times, they have not only maintained scientific output but increased it in some areas. For example, CEH peer review publications have increased by 21% this year over last.

Under the leadership of its Director, Professor Jim Wallace, CEH's Institute of Hydrology has had an excellent year. During the year, the Institute has contributed fully to the Centre's Science Programmes and has joint research projects in place with all the other CEH Institutes. Further details of these scientific activities are presented in this report.

This year's annual reporting follows the arrangement established last year, whereby the CEH Annual Report provides an overview of our scientific progress and principal achievements, while the Scientific Reports of the Centre's component Institutes:

Institute of Freshwater Ecology
Institute of Hydrology
Institute of Terrestrial Ecology
Institute of Virology and Environmental Microbiology

present more detailed reviews of the science. I commend this Scientific Report from the Institute of Hydrology to you, together with the overview CEH Annual Report and the complementary reports from the other CEH Institutes.

Professor W B Wilkinson
Director, Centre for Ecology & Hydrology

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Director's Introduction

The importance of water in sustaining a healthy environment has never been more clearly recognised. Evidence of this is the high profile water has been given by numerous national and international agencies, including UK government departments (DFID, DETR, MAFF), the Environment Agency, the recent EU Freshwater Assessment and the United Nations Commission for Sustainable Development. Closer to home, 1998 saw the highly successful British Hydrological Society conference at Exeter addressing the key issues concerned with *Hydrology in a Changing Environment.* Institute staff were involved in all of these national and international ventures, helping to deliver progress in the hydrological sciences and set the future research agenda.

It has been another excellent year for hydrological research: IH staff have made basic scientific discoveries and delivered novel applications for solving important environmental problems. This second annual Science Report contains a number of examples of this progress. Research into the bio-physical processes which control energy and gas exchange at the land surface continues to explore important new areas. Northern latitudes, where vast areas of wetlands may be emitting huge amounts of greenhouse gases, are now being investigated. In collaboration with Scandinavian and Russian colleagues, field experiments have now been established in Finland and Western Siberia. Initial data are revealing the critical role that the hydrology of these areas plays in controlling the emission of carbon dioxide and methane. At a completely different scale, and back in the UK, IH scientists have been collaborating with the Institute of Terrestrial Ecology in developing new field methods for estimating the amount and vertical distribution of foliage in forests. These techniques can provide hydrological and ecological models with the parameters they need without resort to laborious destructive sampling.

It has been a landmark year for catchment research at IH. The results of 30 years of observations at the Plynlimon catchments in Wales were brought together in a Special Issue of *Hydrology and Earth Systems Science.* Like all good scientific investigations, the analyses presented challenged some of the initial assumptions about these catchments: Were they really impermeable? Is there a climatic signal emerging? Other long term catchment work at IH was also reviewed during the year, with the Coalburn catchment in northern England revealing just how long it takes (>25 years) for the full effects of plantation forestry to be seen in the water balance. IH commitment to catchment research continues. Large investments are being made in the equipment monitoring the Plynlimon catchments and new research programmes for lowland catchments are being developed.

Much progress has also been made in water quality research. New projects have looked at the processes controlling the transfer of pollutants such as nutrients and pesticides to rivers. The latest findings indicate that although point sources of phosphorus from sewage works have been reduced, there are still significant diffuse sources. The pesticide studies have shown that after rainfall several agricultural chemicals appear in rivers at concentrations above the EU guidelines for drinking water. However, tests of this polluted water have not yet shown up any toxic effects.

Environmental impacts are forming an increasing part of the IH research portfolio. An example is the recent joint study with HR Wallingford and TAMS UK to look at extending the life of the Tarbela dam in Pakistan. This reservoir is being affected by sedimentation which is threatening vital hydropower and irrigation facilities. Although the proposed engineering solutions are both expensive and potentially environmentally damaging, they are less so than the alternative of constructing new thermal power stations to compensate for the loss of energy should Tarbela fail.

A successor to the 1975 *Flood Studies Report* is now almost complete. The new scheme, called the *Flood Estimation Handbook* (FEH), is currently being tested externally and includes many novel aspects including new methods for estimating river flow peaks. The production of the handbook — and accompanying software and digital catchment data — is very timely, given the heightened concern over flood estimation resulting from disastrous floods in central England and parts of Wales last Easter. The FEH has ventured into new territory by recommending a method in which flood data are pooled according to catchment similarity rather than geographical position. This approach should revolutionise regional frequency analysis.

IH is also studying the potential impacts of climate change on flooding. Most of the studies so far have looked at impacts on average flows, but the IH study has focused on extreme flows. Initial analyses suggest that if future rainfall scenarios are correct, then there may be large changes in both the magnitude and frequency of flooding in the UK.

The collation, quality control and dissemination of hydrological data also remain a central remit of IH. The past year has seen much innovation here too, with the first electronic *Hydrological Yearbook*, and the completion of the impressive LOIS environmental data handling system. The electronic yearbook not only saves on publication costs, but allows much wider access to this important annual compendium of rainfall, river flow, groundwater and basin evaporation data. Again, the cooperation of the British Geological Survey Hydrogeology group at Wallingford has been invaluable.

The LOIS data system is unique in its ability to handle and display data simultaneously from diverse parts of the environment, often obtained at very different time and spatial scales. Already the LOIS data viewer is available in CD format, complete with its intelligent query software. The successful creation of this type of database is an important step in developing the ability to build the 'Earth System' models called for in NERC's science strategy *Looking Forward*.

This short introduction cannot do justice to the full range of excellent work carried out by IH staff in the past year. An indication of the overall productivity can be gleaned from the publication list in Appendix 4. 1997 saw a highly commendable 26% increase in refereed journal publications by IH staff and data collected to date show that this level of publication output has been sustained during 1998. I encourage readers not only to peruse the rest of this report, but also to study, comment on and debate our scientific findings.

Jim Wallace

The Science Programme of CEH provides a base that underpins national and international requirements in the terrestrial and freshwater sciences. The Programme is wide-ranging and is divided into ten component Programmes, all of which address issues of current environmental relevance and important scientific challenges. The Programme as a whole involves extensive collaboration with academic organisations throughout the world and with international research programmes.

CEH Science Programme

1: Soils and Soil–Vegetation Interactions

This programme is designed to improve our understanding and ability to model key soil processes controlling the transformations of materials within soils and the flux of water through the soil–vegetation–atmosphere continuum.

2: Land Use Science

This is aimed at promoting an integrated approach to land use science that is applicable to the wide range of user community requirements. The programme's themes will be developed to provide the basis for large-scale, long-term analytical studies of major land use change.

3: The Urban Environment

This relatively new programme aims to extend the interdisciplinary knowledge base and to understand the key environmental patterns and processes in urban situations and particularly change due to human activities. This knowledge is required to plan more sustainable urban environments.

4: Freshwater Resources

Increasing demands on freshwater resources have resulted in the need for a scientific basis for the effective strategic and sustainable management of freshwater resources. This programme will address this by integrating CEH research in the areas of water quantity, water quality, and the ecological aspects of freshwater systems.

5: Biodiversity

Aimed at improving our understanding of microbiological and biological resources at a range of spatial scales. The research considers the underlying processes and resulting functions, and directs knowledge to the sustainable management of biodiversity.

6: Pest and Disease Control and Risk Assessment for GMOs

The primary aim of this programme is to undertake research in the provision of novel pest and disease control strategies whilst addressing any possible risk to the environment. The use of molecular biology is essential to maintain a novel and progressive approach to the themes of pest control and animal disease control.

7: Pollution

This programme is aimed at developing a better understanding of generic processes such as atmospheric transport, fluxes of pollutants and the fate of pollutants, in order to predict more accurately the likely impacts on environments and organisms.

8: Environmental Risks and Extreme Events

This research programme will develop understanding of how environmental extremes affect mankind and the natural environment, developing quantitative, predictive tools to describe these effects, and contributing to mitigating measures.

9: Global Change

This programme will help to reduce uncertainty in the magnitude of global change and its impacts. The research is focused on improving the accuracy of global change predictions through measurement programmes, the development of scaling-up methods and models, and the identification of ecosystem responses.

10: Integrating Generic Science

Programme 10 has been designed to provide a research framework for those areas of CEH science which underpin the nine other programmes (e.g. providing the data and the technological support), as well as conducting its own fundamental research.

The following section of this Scientific Report describes research that is currently being carried out in eight of the ten programmes by the Institute of Hydrology. Further details of the themes and issues that make up each of the ten Science Programmes are listed in Appendix 3 of the CEH Annual Report.

Most of the world's vegetation grows in mixtures. It is therefore important to be able to model the water use of these systems correctly to predict the responses of vegetation to different management options and/or global change.

A major control on water use by vegetation is the amount, distribution and efficiency of foliage in canopies. Methods and approaches which do not rely on time-consuming, destructive methods need to be developed.

Soil and soil-vegetation interactions

Figure 1. ICRAF colleagues measuring of soil water content in a *Grevillea robusta*/ maize agroforestry system with an IH neutron probe soil moisture meter.

CONTROLLING WATER USE OF AGROFORESTRY TREES BY PRUNING

Agroforestry is often promoted as a sustainable agricultural production system whereby woody plants are grown in combination either with agricultural crops or with pasture and livestock. Agroforestry therefore has the potential to increase yields by obtaining two or more farming products from a single piece of land. Success will be limited by competition for resources between trees and crops, particularly for light and water, so a key research objective is to find management strategies such as tree pruning to minimise this competition.

We have been collaborating with the International Centre for Research in Agroforestry (ICRAF), on a study of the competition for water in a hillslope agroforestry system. At the ICRAF research station at Machakos, Kenya, 20 m × 20 m plots were planted with silky oak *Grevillea robusta* (a popular tree among East African farmers) and/or maize, in the following arrangements:

- Sole tree treatment with trees planted in a 3 m × 4 m grid pattern without any understorey crop;
- Agroforestry (tree + crop) treatment: trees planted in the same 3 m × 4 m arrangement, but with an understorey of maize planted in rows 1 m

apart, approximately 0.3 m between plants in a row;

- Sole crop treatment: Maize planted in the same arrangement as in the agroforestry plots, but without an upper storey of trees.

Using arrays of neutron probe access tubes, soil moisture content was measured at weekly intervals throughout the soil profile in all three treatments (Figure 1). In the period following establishment of an agroforestry system, and when the tree height is still small relative to the height of the crop, competition for light and water is very different from later on when the trees are nearing their harvest size. If the trees are pruned at all at this early stage, it is to ensure that the trunks will grow straight, and thus have a higher economic value, or else to provide fodder for livestock during the dry seasons. Pruning later on in the lifetime of the system, although providing fodder, also acts as a means of regulating competition for light and water.

Closely planted trees on shallow soils, such as we had in this experiment, will exploit almost the entire soil volume with their extensive root system. Any annual plants, including the maize crop in this case, have to try and establish their root systems in the face of extreme competition from the trees. Severe tree canopy pruning, as practised by many Kenyan farmers, substantially reduces the leaf area on each tree available to evaporate water, hence reducing the overall water demand of the tree. If pruning is carried out immediately before the crops are planted, crop root systems can develop in the face of reduced tree/crop competition for water.

Figure 2 demonstrates the effect of pruning the tree canopy in the Machakos trial on the available water throughout the soil profile (0.1 to 1.7 m). The changes in soil water content in the agroforestry system (trees + maize), as determined from series of neutron probe data, are compared with changes in plots with either trees or crops grown alone.

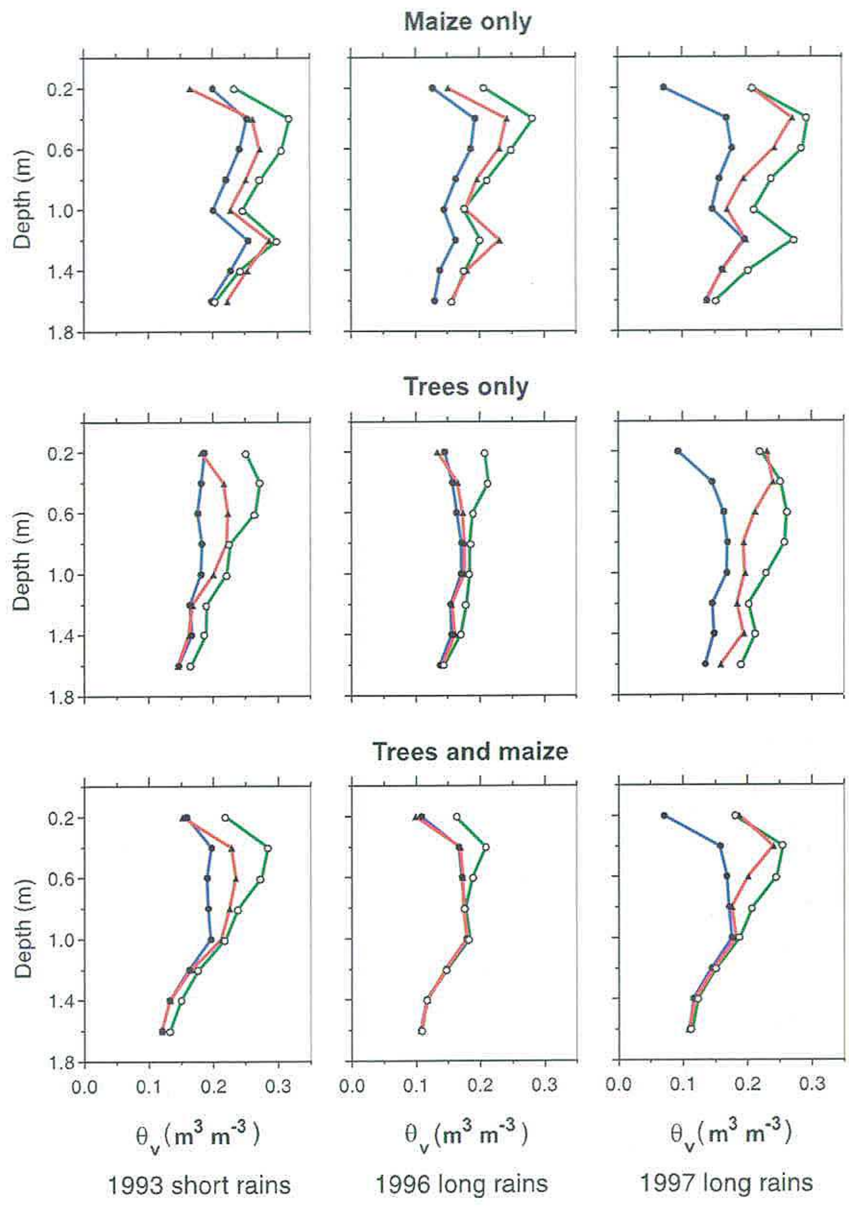


Figure 2. Changes in soil water content profiles (θ, m^3 m^{-3}) in the three treatments following rainfall events in 1993 (when the trees were young), 1996 (before radical pruning) and 1997 (after pruning). Data are mean values for each treatment, a week before rain (▲ / red), one or two weeks after rain (○ / green) and four to five weeks after rain (● / blue).

Tree pruning is a powerful control on the water balance in agroforestry systems

The graphs on the left-hand side show changes occurring during November and December 1993, when the trees were only two years old and not yet large enough to out-compete the crops for water. The increases and decreases in soil water content of the whole 1.7 m soil profile (Table 1) were smaller under maize, either grown alone or with trees, than when the trees were grown on their own. Ground cover at this stage was largely dominated by the maize crop, and greater recharge in the tree-only plots reflects less canopy interception.

Table 1. Increases and decreases in soil profile water storage (mm) for each of the graphs in Figure 2

	1993 Short rains		1996 Long rains		1997 Long rains	
	25 Nov –9 Dec	*9 Dec –23 Dec*	*28 Mar –11 Apr*	*11 Apr –2 May*	*20 Mar –17 Apr*	*17 Apr –8 May*
Sole crop	+ 66.5	- 37.6	+ 84.5	- 20.2	+ 130.4	- 57.3
Sole tree	+ 79.2	- 52.1	+ 43.2	- 37.8	+ 132.9	- 44.0
Tree + crop	+ 69.9	- 45.5	+ 24.2	- 25.8	+ 70.9	- 20.7

The middle set of neutron probe profiles were recorded during March and June 1996, when the trees had reached a height of 8 m and with the maximum canopy size observed during the experiment. The soil in the sole crop wetted up completely, with drainage occurring to below 1.7 m. Little recharge occurred below 1.0 m in the tree+crop plot, and no drainage was observed beyond 1.7 m in either plot containing trees. This was attributed to intense abstraction in the top 1.0 m of soil.

The tree canopies were heavily pruned after this season, following local management practices, removing almost 90% of the canopy volume. The right-hand series of neutron probe data were recorded following pruning, during March and June 1997. Pruning doubled the rainfall input to the soil in the tree only plots, relative to the input to the sole crop plots, and increased it by 25% in the agroforestry treatment. These increases were attributed to reductions in both the canopy rainfall interception, and in soil water abstraction by tree roots.

This study shows that pruning can be a powerful means of controlling the water balance of agroforestry systems. Removing substantial amounts of the tree canopy just before the crop was planted reduced the water demand of the tree component and resulted in a similar degree of recharge to the crop rooting zone as when the trees were younger. The crop also then produced an acceptable economic yield in the following two growing seasons.

Contact Nick Jackson

WOODLAND CANOPY DESCRIBED FROM LEAF LITTER

The structure and functioning of any vegetation canopy plays a key role in the control of mass and energy fluxes between the surface and the atmosphere. Total leaf area index is the principal parameter by which the canopy is quantified and for many applications this parameter will provide an adequate description of the canopy. However, the efficiency of many physiological processes varies within a canopy and there is a need for additional information about the vertical distribution of foliage and any associated variation in structure, chemistry and leaf physiology.

If there is access to the canopy, some of these leaf structural and chemical properties can be sampled directly, but when there is no access, a potentially useful alternative is to estimate canopy functioning and its spatial variability from analysis of leaf litter.

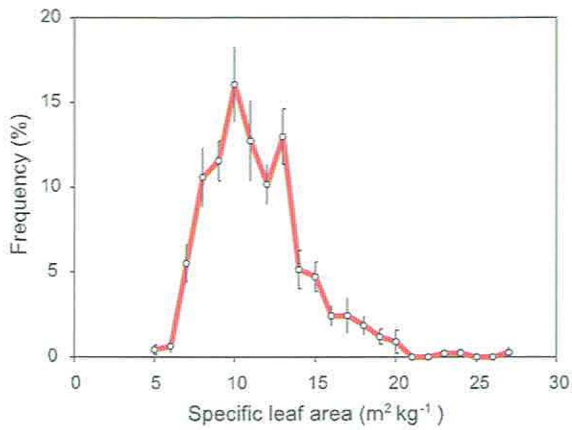


Figure 4. Frequency distribution of specific leaf area in oak leaf litter samples from collections at Wytham Wood, Oxford in 1996

Vertical profiles of living and senesced leaf samples were taken through the canopy of a deciduous woodland at Wytham, just outside Oxford, dominated by oak (*Quercus robur* L). Wytham Woods are owned by Oxford University and are a NERC-sponsored site in the Environmental Change Network. Collaborating with Mike Morecroft (ITE) we have been using an extensive scaffolding walkway system to gain direct access to the crowns of several trees. The samples, organised into specific leaf area classes, were ground to powder and analysed for nitrogen (N) and carbon isotope discrimination (^{13}C). The vertical distribution of leaves within the oak canopy was estimated by counting touches with the canopy from a vertically dropped plumbline at several sampling points on the walkway.

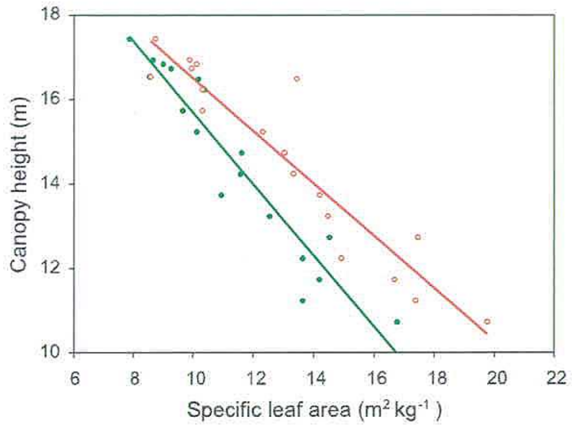


Figure 5. Relationship between canopy position and specific leaf area of green leaves (green) and senesced leaves (red), Wytham Wood, Oxford

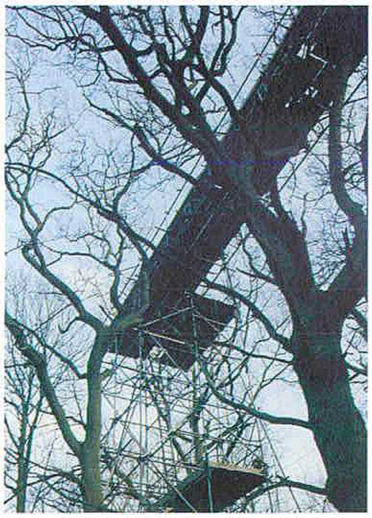


Figure 3. Part of the scaffolding walkway in Wytham Woods.

Leaf litter was collected from late summer to mid-winter in 1996 and around 800 leaves were individually measured for dry weight and area to calculate specific leaf area (SLA; Figure 4). Chemical analyses were also performed on SLA classes in the litter. Figure 5 shows the variation of SLA with height for leaves taken through the oak canopy in early October 1996, when the leaves were green, and November 1996, when they were senescent. At both times there is a highly significant negative relationship, with SLA decreasing linearly with increasing height in the canopy, *i.e.* going up through the canopy, the ratio of leaf area to weight decreased.

Leaf litter has potential as a powerful diagnostic tool, since some properties such as nitrogen content and specific leaf area are correlated with physiological behaviour, particularly maximum photosynthetic rates

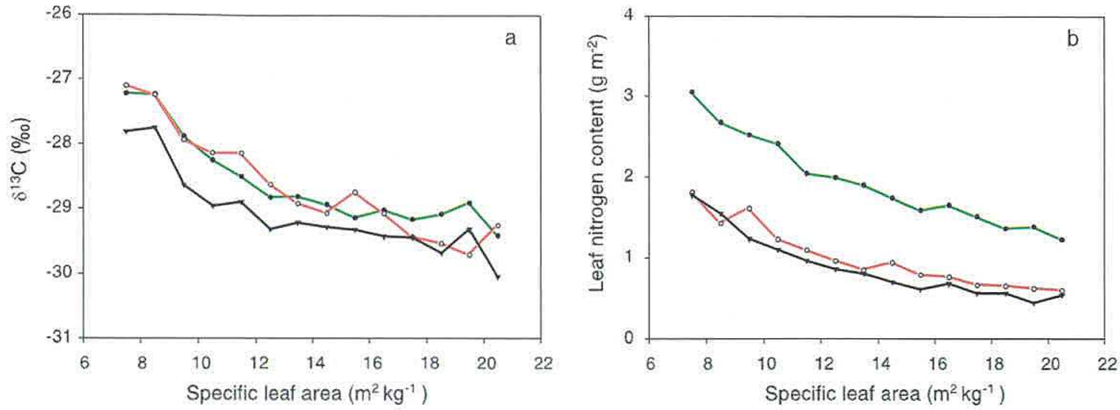


Figure 6. Relationship between specific leaf area and (a) ^{13}C and (b) leaf nitrogen content litter leaves of living canopy leaves, (green); senescent canopy leaves (red) and litter leaves (black) in 1996.

Figure 6 shows that ^{13}C and leaf N decline systematically with SLA in green, senescent and litter leaves. The difference of around -2‰ in ^{13}C between leaves of largest and smallest SLA, which correspond to the highest and lowest canopy position, is similar to the gradients in ^{13}C reported for canopies of a range of forest types. The general view is that vertical differences in ^{13}C of leaves in forest canopies are strongly associated with changes in the ratio of CO_2 concentrations in the external atmosphere and leaf intercellular spaces, caused by variation in photosynthetic characteristics along environmental gradients in canopies and changes in hydraulic architecture within tree crowns, rather than to vertical gradients of ^{13}C of the air within the canopy. We have observed differences in the litter chemistry between 1996 and earlier studies in 1993 which relate closely to known soil moisture and climatic differences between the two years.

Estimates of the frequency distribution of the vertical position of leaves from the SLA distribution in the litter and the information about the position of leaves of that SLA in the canopy agreed very well in relative terms to the direct measurements of canopy density.

This study shows that analysis of forest litter can be used to reconstruct the vertical profile of leaf properties in the living canopy. There is considerable scope to extend this work. It will be necessary to know the relationships between living leaf properties and those in the litter for a wider range of species and conditions. To allocate the foliage spatially, the height and depth of canopy will also need to be known, and ways of doing this without canopy access need to be investigated. Leaf properties will vary at any particular height because of the important influence of different radiation conditions on leaf properties. A final question is to what extent the height distribution of leaves matches variations in other conditions that also influence leaf properties.

Contact: John Roberts

The Institute's research catchments have played a key role in securing general acceptance by the forest and water industries of the practical significance of the much higher evaporation losses from forests than from shorter vegetation. In wet, upland climates the rate of evaporation of water intercepted on tree foliage is much higher than that from grasses due to the greater aerodynamic roughness of the taller forest canopy generating air turbulence to transport the water vapour away from the vegetation surface. Water resources — stream-water supplies and groundwater recharge — are diminished as a direct consequence. This general principle is applicable for forested areas around the world. Given the extensive research facilities available in these catchments, they have naturally become the focus for additional investigations, such as water chemistry and sediment studies, in addition to their use as an open air laboratory for teaching and research purposes.

Land use science

COALBURN: 30 YEARS YOUNG

The smaller study at Coalburn in Northumberland was originally intended to deal just with the early hydrological impacts of afforestation. The research programme has subsequently expanded and developed into a continuing study of forestry growth effects, providing a unique British study from planting through to canopy closure. It is now intended to continue to the felling of the crop around 2010. The Coalburn study has shown very clearly the different hydrological impacts of forestry drainage and forest growth, and demonstrated for the first time the potentially very long term influence of the ground cultivation.

The first full year of study was 1967, when the 1.5 km² study area comprised short, moorland vegetation. After a five-year pre-forestry 'baseline' period, the catchment was plough drained in 1972; in the following year 90% of the catchment was planted with coniferous species, principally Sitka spruce *Picea sitchensis*.

In the early years of forest growth the pre-planting forestry drainage dominated the hydrology and the

This unique study of forest development — from planting to canopy closure — finds the hydrological behaviour of plantations to be different from that derived from studies of mature trees alone

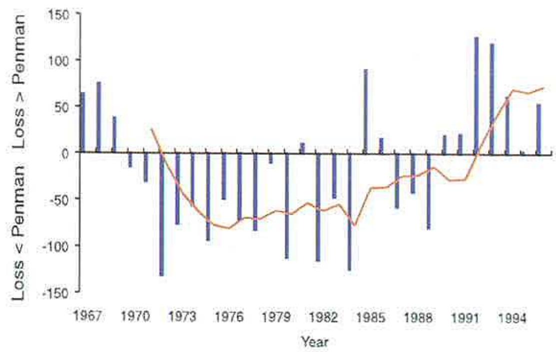


Figure 7. Annual difference between actual evaporation losses (precipitation minus streamflow) and Penman potential evaporation values (mm), together with 5-year moving average.

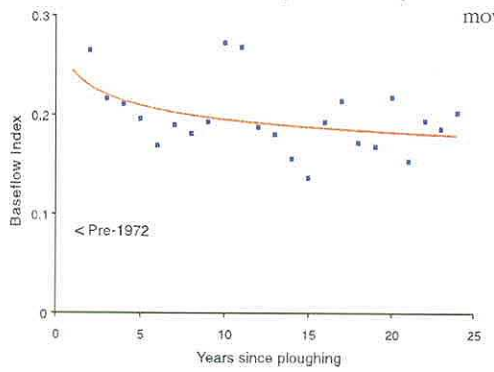


Figure 8. Decline in annual Baseflow Index values since afforestation. The pre-forestry level is shown. At current rates of change the BFI will remain above the pre-forestry level for the remainder of the cropping cycle.

observed changes were quite different to those normally associated with forestry. Peak flows were enhanced and baseflows were augmented. Evaporation was initially reduced as a result of the extensive ground disruption by the drainage, and although it slowly increased with tree growth, the values were depressed for an unexpectedly long period — over one-third of the expected commercial life-span of the forest. The forest growth (Yield Class 12) is fairly typical of upland areas.

Current measured forest interception losses (for 10-12 m tall trees) are about 25%, which is lower than values of about 35% obtained elsewhere in the UK for similar climatic conditions, but more mature trees than those at Coalburn. These results suggest that significant areas of plantation forests may function hydrologically in very different ways to what is generally assumed from studies of mature forests.

Details of the hydrological studies over 30 years at Coalburn (which include many aspects of water quality and soil moisture as well as water balance and extreme flows) are given in IH Report No. 133.

Contact: Mark Robinson

QUANTIFICATION AND CAUSES OF UPLAND EROSION

MAFF has recently commissioned research by CEH (IH, IFE and ITE), Cranfield University Soil Survey and Land Research Centre, and Silsoe College to quantify the extent and causes of soil erosion in the uplands of England and Wales.

The role of this Institute within this project is to enhance the existing long-term suspended sediment monitoring network within the IH Experimental Catchments at Plynlimon. This includes additional continuous turbidity monitoring on the Afon Cyff, an unforested moorland/grassland headwater catchment of the River Wye (Figure 9). The high resolution (15-minute) turbidity and flow data are then used to collate a continuous record of suspended sediment flux from the catchment, and thereby create an integrated measure of surface erosion within its 3.13 km^2 area.

Figure 10 shows the 1997 rating curves of suspended sediment concentration against discharge for the flow gauging sites with turbidity monitoring. This reveals that suspended sediment outputs decrease in the order: *Nant Tanllwyth > Afon Hafren > River Severn > Afon Cyff.*

The differences in suspended sediment outputs between the afforested catchments in the Severn basin can be explained by the positive correlation of particulate outputs with the proportion of the catchment area affected by recent timber harvesting operations. Suspended sediment outputs from all afforested catchments are higher than from the unforested moorland/grassland Afon Cyff catchment.

The existing manual streamwater sampling programme has also been enhanced to include flood sampling at all flow gauging sites, and subsequent analysis for suspended sediment concentration by vacuum filtration. To integrate the physical and chemical suspended sediment budgets, filtered sediment residue is subsequently analysed for carbon, nitrogen, phosphorus and LOI by the Institute of Freshwater Ecology. Bedload transport is also measured in the Afon Cyff and Nant Tanllwyth to calculate the total sediment yields from these catchments.

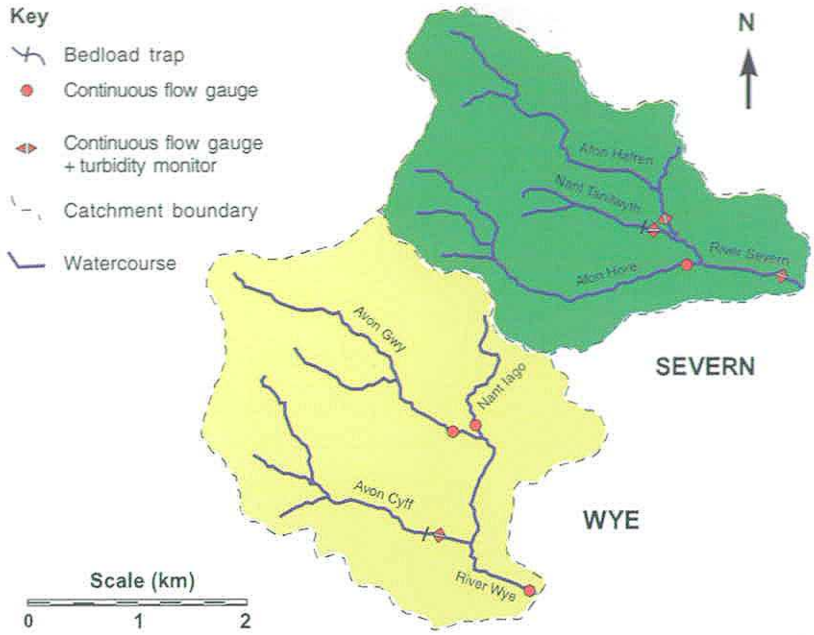


Figure 9. Long-term sediment monitoring network within the Plynlimon experimental catchments

This study will benefit from the historical record of sediment dynamics research within the IH Plynlimon Experimental Catchments since 1972. An accurate record of agricultural practice is available, as good links have been maintained with the single landowner of the Upper Wye headwater area since records began.

As well as providing a measure of surface erosion, catchment sediment dynamics can enable the significance of soil erosion to upland receiving waters to be assessed. Linking catchment surface impacts with the other investigations being undertaken for this project will provide an integrated approach to the assessment of upland soil erosion.

Contact: Stephen Marks

Monitoring sediment dynamics helps to assess the impact of soil erosion on upland receiving waters

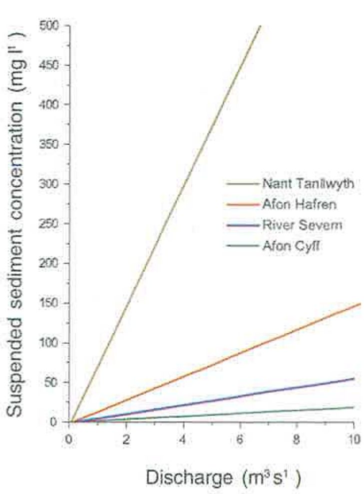


Figure 10. 1997 rating curves of suspended sediment concentration against discharge

The hydrology of urban areas is of increasing concern. There is a need for more efficient and sustainable water management methods to protect local water resources, to optimise the use of surface and groundwater, to control local storm and pollutant runoff, and to help create attractive urban environments. In addition to commissioned studies on urban flood runoff, one of which is described below, the Institute's urban hydrology programme includes core studies on modelling urban water balances and a new project on sediment balances and channel habitat opportunities as part of the NERC Thematic Programme, URGENT.

The urban environment

SCHEME — an IH model to assist with more effective flood control strategies

URBAN RUNOFF IN MIXED URBAN/RURAL CATCHMENTS

It is widely recognised that urbanisation can increase the volume and speed of flood response, so drainage engineers often use storage reservoirs, tanks and ponds to 'balance' the impact. However, the necessity and effectiveness of this storage is rarely assessed on a whole-catchment basis, particularly in larger catchments with several storages and mixed land-use.

Methods for assessing T-year floods in such catchments are poorly defined, and detailed monitoring for model development and verification are virtually nonexistent. This study aimed (a) to establish a record of flood response throughout a complex urban/rural catchment, (b) to show the advantages of a sub catchment based approach to flood modelling, and (c) to assess how the system of flood storages had affected catchment-wide response.

Working with the Environment Agency Thames Region, runoff has been monitored at up to 15 sites within the 52 km² catchment of the Cut at Binfield for a period of four years. Figure 11 shows land use in the catchment, with the urban area — as defined by the *Flood Studies Report* (FSR) — amounting to 29% of the total. This includes the new town of Bracknell, with 18 major storage ponds and lakes.

Runoff monitoring made extensive use of 'sewer survey' loggers, based on pressure transducers to measure depth and Doppler sensors for velocity. The data

Understanding and modelling hydrological processes are essential for estimating the spatial and temporal distribution of freshwater resources. A wide range of innovative commissioned studies has been carried out throughout the world, including resource assessment at the continental, country and basin scale, hydropower design, habitat assessment and estimating river flow distributions at the European scale. In response to resource and environmental pressures on permeable systems, new initiatives have focused on understanding both water quality and quantity pathways between ground and surface water systems.

Freshwater resources

ESTIMATING WATER AVAILABILITY FOR SMALL-SCALE HYDROPOWER PRODUCTION

A key aspect of the design of a small-scale hydropower scheme is to determine the hydrological conditions at the proposed site. Many potential sites are in remote areas, where flow measurements — upon which an assessment could be made — are limited or unavailable. The Institute of Hydrology has recently developed a PC-based package, which allows not only the hydrological characteristics but also the hydropower potential to be determined at any site. The package, HydrA, is the result of a three-year research project funded by the European Small Hydropower Association (ESHA) through the Altener programme of the European Union (DGXVII).

The software builds on existing techniques for assessing hydrological regimes that have been developed by the Institute of Hydrology over many years. The techniques focus on the estimation of flow from catchment characteristics at ungauged locations and have previously been applied to the IH Micro LOW FLOWS software, a tool used extensively within the UK water industry for catchment management and water resource planning purposes. Through the development of HydrA, the techniques have been applied to other parts of Europe. The software has already been completed in Spain, Italy and the

New PC-based software to assess hydropower potential at any site

UK and is presently being developed specifically for Austria, Belgium, Portugal and the Republic of Ireland.

HydrA is presented as a menu-driven software package and incorporates regional flow estimation models and databases of climate and hydrogeological response characteristics, plus algorithms for calculating the generating capacities of turbines and annual power output for the site. The regional models are developed for each country based on available hydrometric, meteorological and physiographic data supplied by partner organisations in the representative countries. Statistical analysis of the data is used to identify models for estimating mean flow, low flow statistics and pooled flow-duration curves in each country.

The value of the method has been recognised for application in other parts of the world. The Department For International Development (DFID) is presently funding the Institute in a three-year research project to develop the software for two Himalayan regions in India and Nepal. The work is being carried out in collaboration with the Alternate Hydro Energy Centre in Roorkee, India, the International Centre for Integrated Mountain Development (ICIMOD) and the Department of Hydrology and Meteorology in Nepal. The development of regional low flow models in the Himalayan region poses a significant challenge because of the extreme relief and the seasonal effects of the monsoon.

Contact: Gwyn Rees

Figure 14. Irrigation releases from Tarbela Reservoir

MAINTAINING HYDROPOWER PRODUCTION AT TARBELA RESERVOIR, PAKISTAN

Tarbela Dam in Pakistan harnesses the waters of the Indus to provide about half of the country's irrigation needs, and one third of its electricity. However, the life-span of the reservoir is threatened by sedimentation and, since impoundment in 1974, the reservoir has lost over 20% of its gross capacity. Further, with each year's flood inflow, the sediment delta continues to approach the intakes to the power tunnels, threatening to cut off this huge source of energy to the country. IH has been working with TAMS Consultants Inc., New York, and with HR Wallingford to identify options for extending the life of this vital facility well into the next century.

IH provided long-term inflow series to a reservoir sedimentation simulation model operated by HR Wallingford. We then ran a system simulation model to predict the future irrigation and energy benefits which would be derived from the reservoir under either a range of revised operating strategies or various proposed engineering solutions. These included construction of low-level sediment sluices and/or an underwater dyke to keep sediment from entering the power tunnels.

Although the optimum solution involved very major and costly engineering works, the alternative would involve Pakistan in having to construct a large number of thermal power stations to compensate for the energy lost through failure of Tarbela. The environmental costs of this, through the burning of fossil fuels and resulting contributions to global warming, strengthened the planned adoption of the proposed engineering solutions which were both cost-effective, and environmentally sound.

Contact: Frank Farquharson

SIMPLE, ROBUST INTEGRATED HYDROCHEMICAL CATCHMENT MODELS FOR USE IN WATER PLANNING

The large amount of information now available on the factors controlling streamflow volume, timing and hydrochemical characteristics of rivers in the UK and Hungary has led to a collaborative project involving IH, Vituki, Hungary and the University of Utrecht, Netherlands, to develop simple but robust models of catchment behaviour that can be used to predict hydrological and water quality changes in a time of predicted climate change. The project, funded by the EC as part of the Environment and Climate Programme, uses the hydrological modelling expertise of IH and the University of Utrecht to set up a semi-distributed monthly streamflow model based on Utrecht's PC Raster GIS software, behind which operate streamflow generation routines synthesised from myriad process studies carried out in experimental basins across Europe.

Processes involved in the transfer of nutrients to water courses have been studied in depth over many years in the Zala target catchment feeding to Lake Balaton in Hungary, a catchment with a history of water quality problems linked to the heavy use of fertilisers and poor runoff control.

The River Severn catchment to Shrewsbury in UK is also under scrutiny as an example of a relatively pristine environment, which should test the range of applicability of the models developed in the light of the good hydrometric and chemical calibration data available. The advent of GIS systems, especially PC Raster which has been developed specifically as a hydrological modelling tool, has enabled further development of an existing water quality delivery and routing model SENSMOD (written by the Hungarian partners) to operate within a GIS framework. The GIS covers spatially-distributed data on hydrological variables, land use, fertiliser inputs, soil

New model indicates climate change impacts may affect the hydrological regime of the River Severn catchment

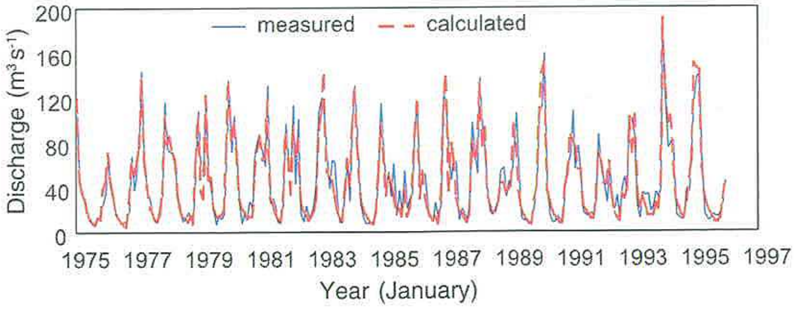


Figure 15. Observed monthly streamflow compared with SEVERNFLOW model values for the River Severn to Montford Bridge, Shrewsbury

nutrient status and soil type, drainage direction and channel networks, and reservoir distribution (supply, amenity and flood control).

Early indications are that climate change may alter the hydrology of the River Severn, with increased rainfall offsetting the higher evaporation rates expected from a higher temperature regime. Extra resources may of course be utilised by increased domestic and industrial demand, by increased irrigation requirements in the lowland portion of the catchment during expected drier summers and with changes in the pattern of crops, and by statutory increases in compensation flows from the main reservoirs, Clywedog and Vyrnwy, for ecological reasons. In Hungary there is expected to be an increase in the incidence of drought, which will provide lower compensation flows from the existing reservoir system and the demand to build new reservoirs to compensate. A reservoir management module is being included in the hydrological model of the Zala to take this into account.

Contact: Jim Hudson

ENVIRONMENTAL ASSESSMENT OF HYDROPOWER GENERATION

Assessing the environmental down-side of hydro-electricity schemes

Electricity is such a fundamental requirement that it is difficult to imagine life without it. For developing countries it is a prerequisite for economic growth. Hydro-electric power is often thought to be environmentally benign. However, the construction and operation of many hydro-power dams have had significant negative impacts on the environment and rural economies. Reduced downstream flooding has destroyed fisheries and starved the floodplain soils of moisture and nutrients. Often the areas worst affected have no electrification and thus local communities lose vital natural resources yet do not benefit from power generation, as witnessed in the Senegal valley.

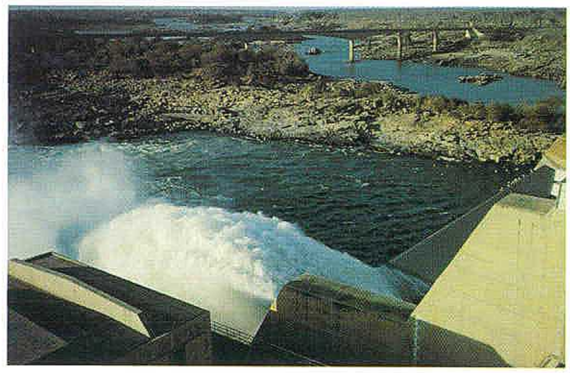


Figure 16. Water being released from Roseires Dam, Sudan

The Institute has provided advice to IUCN (the World Conservation Union) on environmental impacts of large hydro-schemes in Africa and the potential for making artificial flood releases from dams to restore and conserve downstream wetland ecosystems. This integrated approach allows a compromise to be reached between electricity generation and maintenance of a dynamic flooding pattern for the short term economic importance of fisheries and agriculture and the longer term importance of soil fertility and biodiversity. Involvement of local communities representatives in deciding when flood waters should be released, as on the Phongolo River in South Africa, has resulted in great benefits to floodplain users. IH has also been involved in the design of new dams on the Tana River in Kenya. These dams are being specifically designed to make flood releases.

Contact: Mike Acreman

Pollution from diffuse or non-point sources is a major unknown in catchment systems, both in terms of quantification of pollutant loads and in identification of pathways. A thorough understanding of pollutant sources, transport and fate is essential to the management of water resources and underpins the development of catchment scale water quality models which provide the tools for management. Process-based models also enable assessment of future scenarios describing changes in pollutant input, land management or other external drivers. The use of models in agreeing international scale reductions in acidic emissions is a prime example.

Pollution

PHOSPHORUS DYNAMICS IN THE RIVER KENNET

Eutrophication (nutrient enrichment resulting in excessive plant growth) is a growing problem in UK lowland rivers during the summer, often as a result of changes in the balance between sewage inputs and river flow. Phosphorus is frequently the limiting nutrient for summer phytoplankton growth in freshwater, and sewage effluent is a major source of phosphate in many lowland rivers. In the south of England, low river flow conditions in recent summers have reduced the dilution of effluent discharges and increased phosphate concentrations. This has, in part, prompted a concerted effort to reduce phosphorus discharge from sewage works. The Urban Wastewater Treatment Directive (Council of European Communities, 1991) dictates that phosphorus discharges from sewage treatment works, serving populations of more than 10 000 and discharging into 'sensitive' (eutrophic) waters, must be reduced unless it can be shown that the reduction will have no effect on eutrophication.

The River Kennet, a tributary of the River Thames, is a chalk stream subject to phosphorus-rich discharges in its upper reaches below the town of Marlborough. At

Detailed monitoring confirms the river water quality improvement through phosphorus removal from sewage effluent

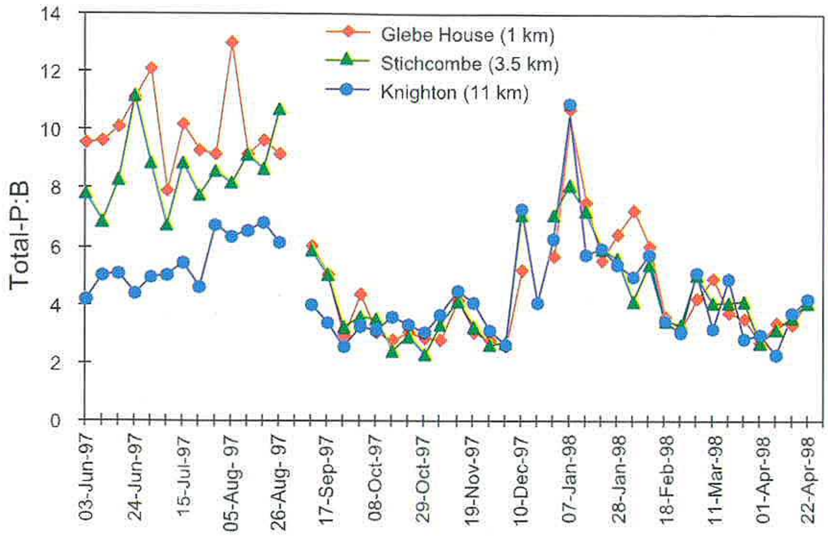


Figure 17. Ratio of total phosphorus to boron concentrations in the River Kennet at three sites downstream of the Marlborough sewage treatment works for weekly samples collected between 3 June 1997 and 22 April 1998

the end of August 1997, Thames Water plc installed equipment to remove phosphorus from the effluent discharged from the Marlborough sewage treatment plant. Before this (in June 1997) IH began a water sampling programme, in collaboration with the University of Reading, to facilitate examination of the 'before and after' effects of phosphorus removal. Ratios of total phosphorus (TP) to boron (B) in the River Kennet have been used to examine the response to changes in point-source phosphorus inputs. 'Total phosphorus' includes both the dissolved and exchangeable phosphorus attached to the surface of suspended sediments. Boron in river water exists primarily in a chemically unreactive form (borate), derived from sewage effluents, which are enriched with boron as a result of soluble boron-containing minerals used in detergents and washing powders. Within the Kennet, very low background concentrations of boron in groundwater make this a chemically conservative tracer for sewage effluent.

During the summer of 1997, the general decrease in the TP/B ratio downstream from the sewage works (Figure 17) indicates loss of phosphorus as a result of uptake by aquatic plants or sediments. In September there followed a dramatic reduction in the TP/B ratio at all sites, showing the effectiveness of the phosphorus removal from sewage effluent at Marlborough sewage treatment. During this time, total phosphorus concentrations declined from approximately 750 mg l^{-1} P to around 250 mg l^{-1} P at Glebe House, approximately 1 km downstream of the sewage works. In December, the TP/B ratio increased again and all sites exhibited a similar TP/B ratio. This corresponds with a marked increase in river flow and suggests a diffuse source of phosphorus.

Contact: Helen Jarvie

IMPACT OF PESTICIDES ON RIVER ECOLOGY IN HEADWATER STREAMS

Previous work with ADAS has shown that water draining agricultural land can contain pesticides in sufficiently high concentrations to kill off some aquatic organisms. The Institute is collaborating with the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) in a project funded by MAFF, the Environment Agency and the Department of the Environment, Transport and the Regions to see whether there is a causal link between the routine use of agricultural pesticides and damage to the ecology of headwater streams. Headwaters are of particular interest, because the flora and fauna they support are likely to be exposed to the highest pesticide concentrations in runoff and they represent a large percentage of the habitat available to aquatic organisms.

Streams draining two cereal farms, a fruit farm and a sheep dipping area, on essentially surface runoff dominated soil types, have been chosen to represent a range of agricultural activities. The aim is to collect samples that represent the chemical composition of the water in the headwater streams during high flows and to carry out in situ and laboratory bioassays to determine if the event has caused damage to the indigenous or test animals.

Because the streams being studied respond quickly to rainfall the sampling of the river water is carried out using automatic samplers (see Figure 18). These are triggered by a rise in river level and continue to collect samples on a pre-determined frequency until the river level falls back to normal. The precise time of each sample is recorded on a data-logger together with the rainfall, river level and dissolved oxygen concentration of the stream water. Each of the loggers can be interrogated remotely using mobile telephone links to check the current status of the river flow and the sampling programme without the necessity of a field visit. During the first 18 months of the study 18 pesticides have been analysed in some 29 events. Figure 18 shows concentrations for a selection of these pesticides, together with the stream height, in one of the streams for a sequence of events during May.

So far, no toxicity attributable to pesticides has been detected in any of the event water samples or in the stream bioassays. Samples of indigenous stream fauna are

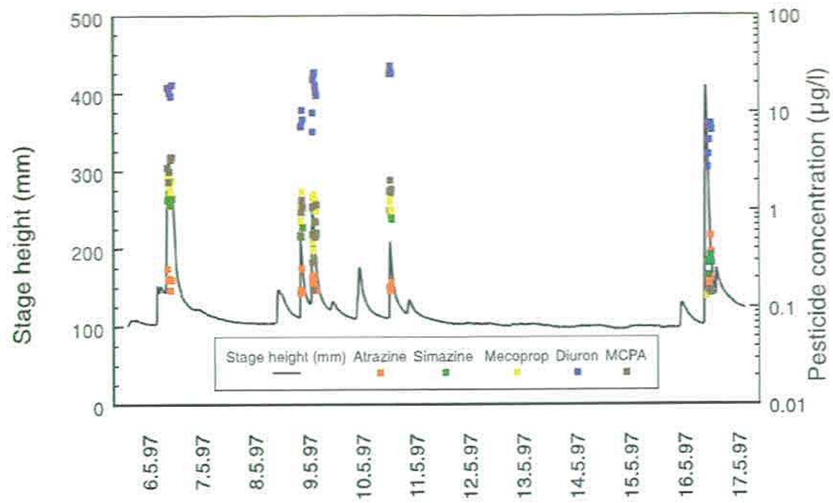


Figure 18. Concentrations of pesticides in the stream draining the Dollymans Farm site following rainfall events on the 6.5.97 - 16.5.97

currently being analysed. Monitoring and testing will continue until June 1999 with increasing emphasis on agricultural insecticides.

Contact: Richard Williams

MODELLING SURFACE WATER ACIDIFICATION AT THE UK SCALE

In support of international negotiations to control emissions of anthropogenic sulphur (S) and nitrogen (N) to the atmosphere, dynamic models have been applied to a range of headwater catchments. These model applications provide estimates of the time lag between achievement of agreed emission reductions and recovery of surface water chemistry. To date, however, such modelling assessments have been limited to case studies in sensitive areas by data availability and the lack of a consistent methodology for more wide-scale application.

As part of the EU-funded DYNAMO project, techniques have now been developed to calibrate

Modelling the impact of agreed emission reductions on the recovery of acidified streams

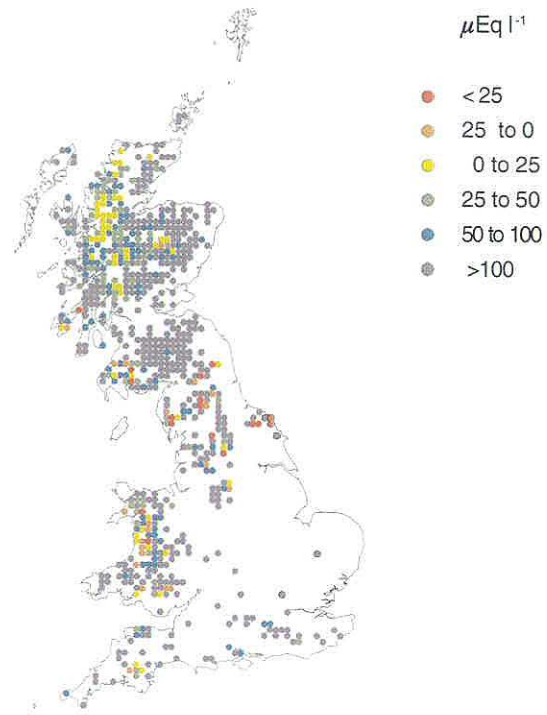


Figure 19. MAGIC-modelled Acid Neutralising Capacity (ANC), 1997

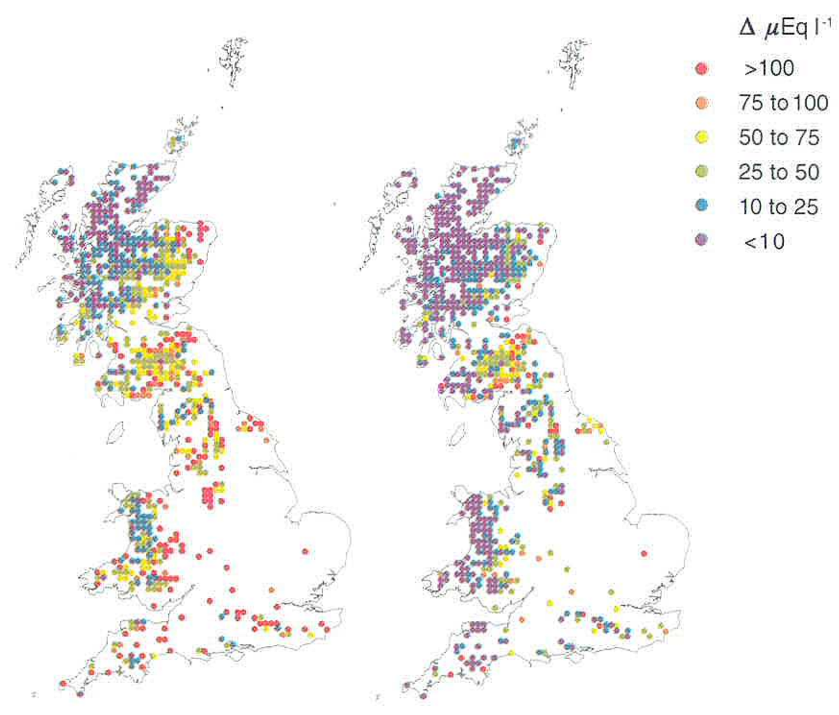


Figure 20. Decreases in Acid Neutralising Capacity (ANC) from 1850 to 1997 (left), and projected recovery from 1997 to 2050 (right)

the MAGIC model for nearly 700 sites across the UK, using spatially consistent databases describing water chemistry, soil physical and chemical properties, rainfall, runoff and deposition chemistry. Present day Acid Neutralising Capacity (ANC) at these sites is shown in Figure 19. Marked regional variations are evident, with the most acidic conditions in areas of the Pennines, North York Moors, Lake District and Galloway.

For each site, the model has been used to reconstruct water chemistry in 1850 (before the onset of industrialisation) and to predict future changes in response to currently agreed reductions in S emission under the Second S Protocol. Decreases in ANC from 1850 to the present day, and projected recovery to 2050, are shown in Figure 20. ANC decline has been greatest in areas of England and Southern Scotland, that have been subject to high levels of acid deposition, and least in unpolluted areas such as north-west Scotland. The most acidified sites historically are forecast also to show the largest future recovery, but in general this ANC increase is predicted to counteract only a small proportion (around 25%) of the historic decline. Many sites may therefore remain acidified (ANC < 0) in the future under current emission scenarios.

Work is continuing to develop the model to incorporate N dynamics to assess the potential response to changes in the input of total acidity (nitrogen and sulphur) in support of new international agreements.

Contact: Chris Evans

The severe widespread flooding in the UK and overseas resulting in huge financial costs and loss of life has highlighted the importance of the accurate prediction, estimation and forecasting of extreme events. The Institute will complete the Flood Estimation Handbook in 1999. Based on an analysis of all flood peak data, it provides new and innovative design methods for flood estimation throughout the UK. IH research is extending risk analysis to include the evaluation of the spatial dependence of extreme events and the impact of natural hazards on ecological systems in cooperation with IFE and ITE.

Environment risks and extreme events

HYREX: HYDROLOGICAL RADAR EXPERIMENT

This was one of our parent Natural Environment Research Council's Special Topics, which ran from May 1993 to April 1997. The broad aim of HYREX was to gain a better understanding of rainfall variability, as sensed by weather radar, and how this variability impacts on river flow at the catchment scale. Six projects were funded, involving groups from the Institute of Hydrology, the Rutherford Appleton Laboratory and the universities of London (Imperial College and University College), Newcastle, Reading (including the Joint Centre for Mesoscale Meteorology or JCMM) and Salford. The projects ranged from research on improved precipitation measurement, using polarisation and vertical pointing radars, through network design of radar/raingauge networks and spatial-temporal modelling of rainfall fields, to rainfall forecasting based on stochastic and meteorological concepts.

The experiment was centred on the Brue catchment in south-west England, with a river gauging station at Lovington measuring flows draining from an area of 132 km^2. The common experimental infrastructure comprised two national network C-band radars at Wardon Hill (Doppler) and Cobbacombe Cross, a purpose-built dense raingauge network, an automatic weather station, an automatic soil water station and the river gauging station. These instruments have provided a continuous record throughout HYREX and data collection is still continuing.

Further instrumentation, deployed on an occasional basis, was scheduled to coincide with a number of one or two-day Intense Observing Periods, triggered by meteorologically interesting conditions, during which

HYREX aims to provide a better understanding of rainfall variability, as sensed by weather radar, and how this variability impacts on river flow at the catchment scale.

radiosonde ascents and aircraft overflights were made, and for which special runs of the Unified Model were made. These instruments included an experimental S-band Doppler dual polarisation radar at Chilbolton and an associated line network of rapid-response raingauges (operated by Rutherford Appleton Laboratory), a transportable vertically pointing X-band radar (operated by the University of Salford), the UK Meteorological Office (UKMO) Research Flight and radiosonde network, and a disdrometer (operated by the Institute of Hydrology). The JCMM provided output from special runs of the UKMO Unified Model (UM).

The dense raingauge network comprises 49 tipping bucket raingauges, with at least one raingauge in each of the 2 km radar grid squares that lie entirely within the catchment. In addition, there are two parallel lines of greater gauge density extending SW to NE across the catchment, aligned with the prevailing wind direction and running from lowland to upland. Within each line there is one 2 km grid square containing a super-dense sub-network of eight raingauges arranged in a square-within-a-diamond configuration: one sub-network is in a lowland area and the other in an upland area.

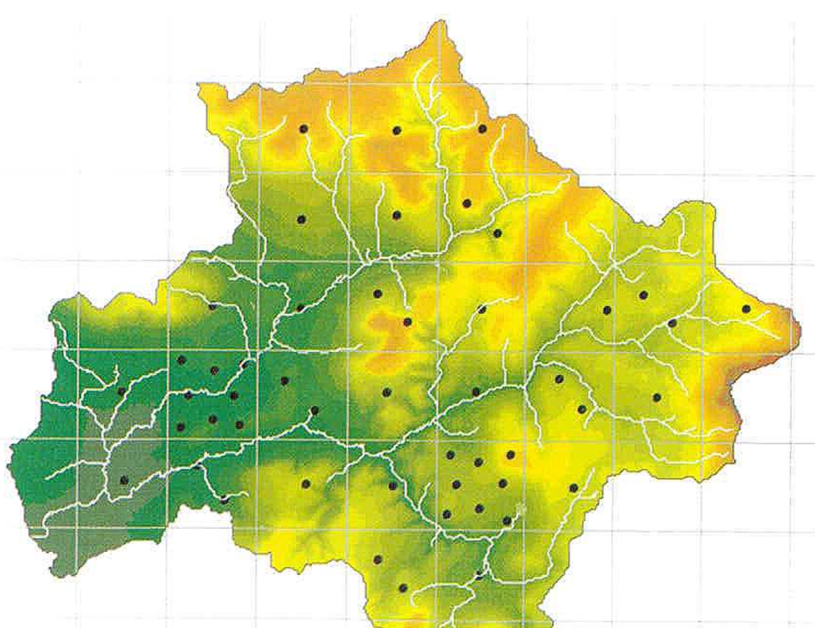


Figure 21. Relief map of the Brue catchment showing the dense raingauge network

The Institute was responsible for the quality control of the dense raingauge network as part of its project concerned with the accuracy of radar/raingauge networks. This project investigated the variability of rainfall as it varies with intensity over the spatial scales of the radar data (2 × 2 km) and the catchment (132 km^2). For the 2 km case accuracy was shown to be related to the accuracy of the areal rainfall estimates themselves. For the higher rainfall situations, variability of around 20 % and 50 % at the 2 km and catchment scales respectively was found. Consideration of radar recalibration by raingauges explored how the use of a single gauge, typically available operationally for a catchment the size of the Brue, affected the accuracy of rainfall estimation. A dynamic raingauge calibration was shown to be only effective over a relatively short distance whereas a long-term climatological correction proves more useful at greater distances. A tapered calibration factor method was developed that behaves as well as the dynamic calibration at close distances and takes the form of the climatological correction at larger distances.

A second project at IH under HYREX investigated a simple two-dimensional rainfall model, based on advection and conservation of mass in a vertical cloud column, for use in short-term rainfall and flood forecasting at the catchment scale during convective storms. The model is capable of assimilating weather radar, satellite infra red and surface weather observations, to obtain frequently updated forecasts of rainfall fields. The results obtained from two convective events over southern Britain show that (i) a simple advection-type forecast may be improved upon by using multiscan radar data in place of data from the lowest scan, and (ii) advected, steady state predictions from the dynamic model, using 'inferred' updraughts, provides the best performance overall

More details on HYREX, including access to the dataset, are available at the NERC British Atmospheric Data Centre web site at http:/ www.badc.rl.ac.uk/data/hyrex.

Contact: Bob Moore and Vicky Bell

DIGITAL DATA AND THE FLOOD ESTIMATION HANDBOOK — AN EXAMPLE

The *Flood Estimation Handbook* (FEH) research programme includes a new statistical method for estimating river flow peaks. The index flood is the median annual flood, QMED, estimated for ungauged catchments by a regression equation based on catchment descriptors.

Although Figure 22 for south-west England looks like a map of watercourses, it is not derived from the stream network. What it actually shows is the drainage paths derived from the IH digital terrain model (IHDTM) for all points draining an area of at least 0.5 km². At each point on a drainage path, the boundary of the catchment draining to that point is calculated. QMED is then estimated from the characteristics of the particular catchment and a map is built up point by point. The plotted drainage path width is proportional to the square root of QMED.

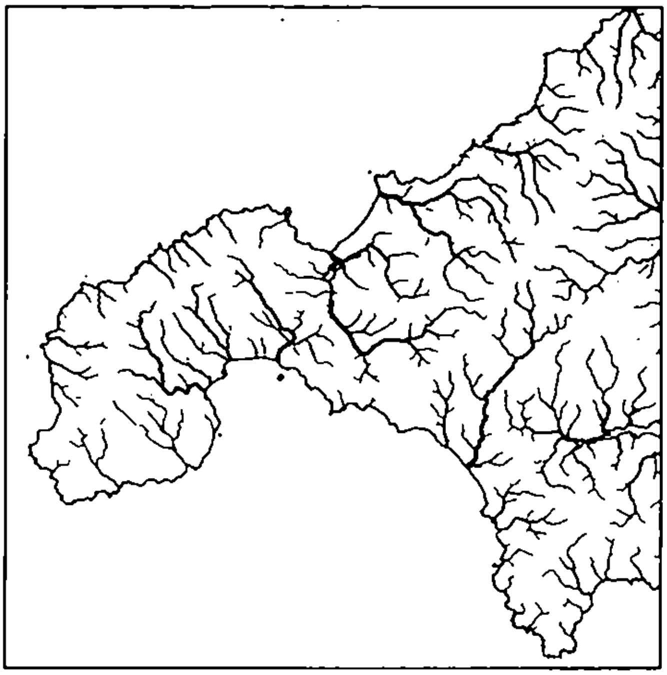


Figure 22 Mean annual flood, QMED, along flow paths

Although the drainage paths appear to increase with catchment size, in fact the map of QMED reflects the influence of soil type, rainfall and flood storage as well as catchment size. The map is derived using a model with five variables. AREA (catchment size), SPRHOST (standard percentage runoff estimated from the HOST soil classification), BFIHOST (baseflow index), SAAR (average annual rainfall) and FARL (an index of flood attenuation due to reservoirs and lakes). All these variables are calculated automatically from digital data with no need to derive them manually from maps.

Contact: Duncan Faulkner

Preview of new method for estimating river flow peaks — from the soon-to-be-published *Floods Estimation Handbook*

NEW ELEVATION-DEPENDENT SNOWMELT MODEL FOR FLOOD FORECASTING

Combining a rainfall-runoff model with a snowmelt module has produced an important additional tool for flood forecasting

An elevation-dependent snowmelt model has been developed for use in upland Britain for flood forecasting and warning. Here, the dynamic nature of snow cover, and the occurrence of heavy rain along with melt, can exert a considerable influence on major floods. The model comprises the PACK snowmelt model linked to a lumped conceptual rainfall-runoff model, the PDM (Probability Distributed Moisture) model. The PACK snowmelt module conceptualises the lying snow as being made up of dry snow that has yet to melt and wet snow which has melted but is still held in the snow pack. When the temperature is above the melt threshold the dry snow melts at a rate proportional to the temperature excess above the threshold and contributes to the wet snow store. Water is released from the wet snow store at a rate dependent on the proportion of the pack that is melted snow, and is transformed into flow at the basin outlet by the PDM module.

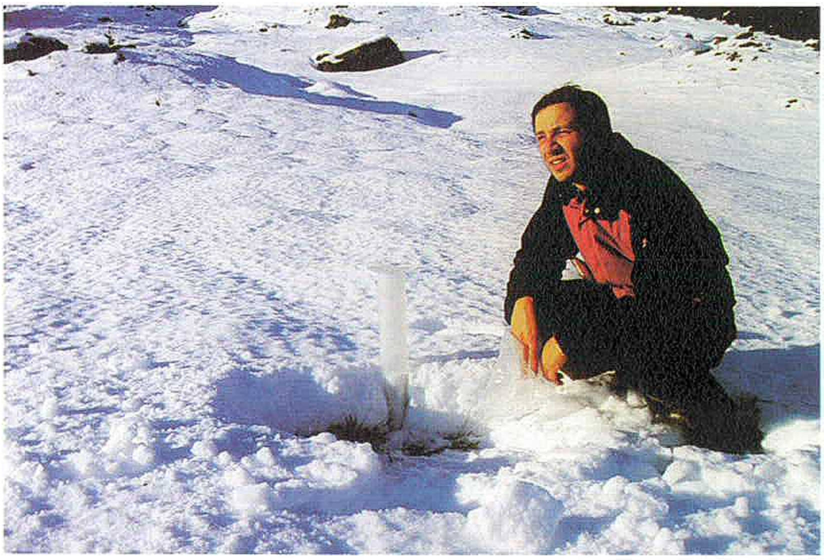


Figure 23. Using a snow corer in the Balquhidder catchment in Scotland

The variation in temperature with elevation in a catchment and its effect on melt can be dealt with by partitioning the catchment into a finite number of elevation zones. Model performance is generally improved through the use of more zones. This result prompted the development of a new formulation that can use either a near-continuous distribution or a finite number of elevation zones derived from a digital terrain model. The new formulation allows the evolution of the snowline over time to be determined along with the water equivalent of the pack and the discharge at the basin outlet.

The new model has been tested on two upland catchments, Monachyle Burn in Scotland (11.4 km^2) and Trout Beck in Northern England (7.7 km^2). Excellent simulations of flow are obtained for both catchments with R^2 values of circa 0.9. A sensitivity study of the accuracy of flow simulations to the number of elevation zones employed suggests using a 30 m elevation range for a zone as a conservative choice. Observations of the position of the snowline in the Monachyle compare very well with model predictions (R^2 values of 0.74 and 0.66 for two snowmelt periods). An assessment was also made of the use of daily snow survey and hourly snow pillow measurements for updating the Trout Beck model. The results suggest that the pillow data, if used with care, can provide as good if not better flow predictions. However, there is a tendency for snow to melt preferentially from the pillow compared to the surrounding vegetation.

Contact: Vicky Bell and Bob Moore

Predicting future change in climate and its impacts on the environment is one of the most important and demanding tasks facing science. The Arctic environment is both vulnerable to global climate change and critical in defining the feedbacks which may amplify or dampen the changes resulting from anthropogenic gas emissions. The most serious impacts of global climate change will not be from different average conditions but from changes in the frequency and size of extreme events — current predictions warn of increases in the return periods of damaging floods.

Global change

ARCTIC HYDROLOGY

The Arctic has been identified as the region that might experience the greatest increase in surface temperature through global warming: this would have important repercussions for hydrology. Although the Arctic is covered in snow for most of the year, it has low annual precipitation, similar to the East Anglian region of the UK. Streamflow mostly occurs over predominantly frozen ground during the snowmelt period. Whether the Arctic becomes warmer and wetter, or warmer and drier, will not only affect the hydrological balance, but — through the unfreezing of the soil — it may also release extra carbon dioxide and methane into the atmosphere. This would increase concentrations of greenhouse gases in the atmosphere and accelerate global warming.

The Land Arctic Physical Processes (LAPP) project is a multi-national experiment, led by the Institute and partially funded by the European Commission. Through a programme of measurements and modelling exercises, LAPP is investigating the physical processes that control the interaction of water, carbon dioxide and methane between the Arctic land surface and the atmosphere.

The Arctic region has a pronounced latitudinal gradient of temperature, precipitation, vegetation cover and permanently frozen ground. To address this variability, similar measurement programmes are being carried out at Ny-Ålesund, Svalbard (79°N), Zackenberg, Greenland (74°N) and Kevo and Kaamanen, Finland (69°N). Sensible heat, evaporation and carbon dioxide fluxes are being measured at each of these

Investigating the physical processes controlling the interaction of water, carbon dioxide and methane between the land and the atmosphere

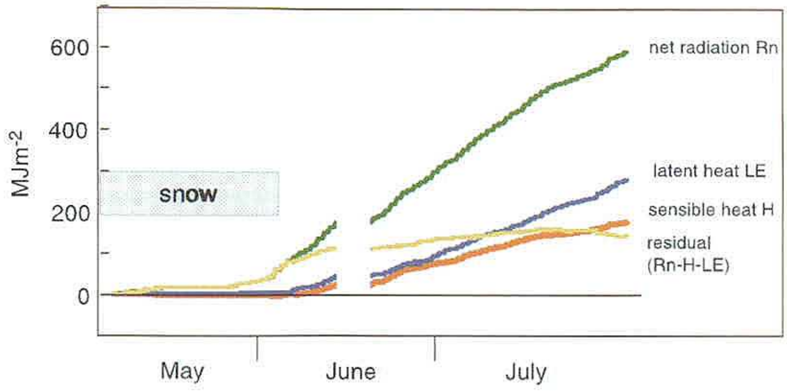


Figure 24. The cumulative energy fluxes at the Kevo mire site during the early summer of 1997

sites, using the eddy correlation method, for the important period from snowmelt through the arctic summer and into the freeze-up in the autumn. Eddy correlation and static chamber measurements of methane have also been taken at the principal sites.

Cumulative energy fluxes of net radiation, evaporation and sensible heat from the IH field site at Kevo are low while snow is still present (Figure 24). The residual term is the energy being used to melt the snowpack. This radiational energy is supplemented by some energy being taken out of the surface atmospheric layer. Once the snow has disappeared, the residual energy continues to increase as energy goes into unfreezing the soil. The residual term stops increasing at the end of June, and during July all the incoming radiant energy is used for evaporation and sensible heat flux.

The site at Kevo (Figure 25) is an elevated mire which consists of raised hummocks and sunken pools created by the action of permafrost. The hummocks are predominantly covered with dwarf birch and berry plants while the pools are filled with sphagnum moss and sedge grasses. Important controls on the evaporation and carbon balance of these different surfaces are their surface temperature and the level of the water in the mire. Figure 26 shows the variation in surface temperature of a hummock and a pool and the air temperature at 3 m. Large differences in the surface temperatures occur during periods of low windspeed. The surface temperature and mire water level will be important variables in predicting the effects of climate change. The major goals are to identify and model the relationships between these and other surface variables in both

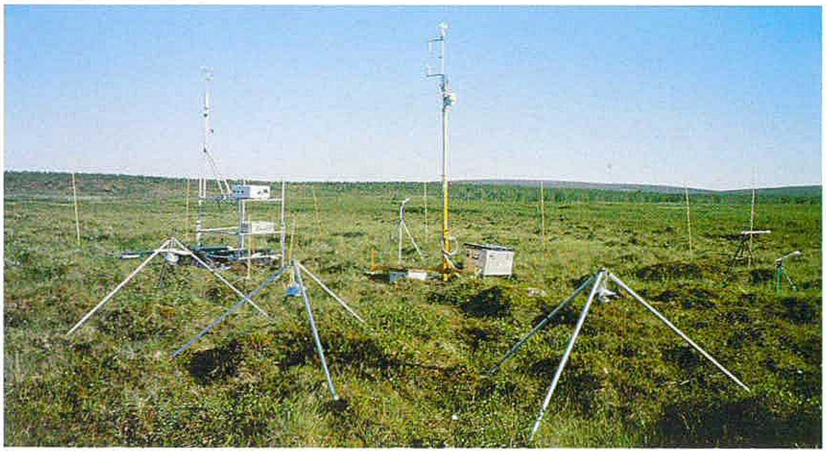


Figure 25. The mire site at Kevo showing infrared surface temperature instruments in the foreground with evaporation, sensible heat and carbon dioxide flux measurement systems behind

hummocks and pools and the evaporation and carbon balance of the mire as a whole.

A second site was set up on a hillslope at Kevo during 1998. Measurements are being made there of runoff from a small catchment and evaporation from the slope: the latter uses the new flux measurement system, based on a three-dimensional anemometer, that was featured in last year's report (page 35). These observations will be used to investigate the hydrological response of a hillslope with frozen soil. Ultimately this description will be included in large-scale simulations of the water balance and river response in high latitude regions.

Measurements from Kevo are also being used to test and improve the current Soil-Vegetation-Atmosphere Transfer (SVAT) scheme used by the UK Meteorological Office in their Global Climate Model. This Meteorological Office Surface Exchange Scheme (MOSES) provides a mathematical description of the interface between the land surface and the atmospheric circulation.

This work has demonstrated that the Arctic is a delicately balanced ecosystem with an inter-annual variability, whereby some areas can switch between being a source or a sink of carbon dioxide, and that the particular hydrology of the area is a major factor in this process. At the Ny-Ålesund site in Svalbard, the timing of the disappearance of the snowpack and the length of the arctic summer, together with changes in the amount and frequency of rainstorms during the summer, have a profound effect upon the growth rates (and hence carbon uptake) of the vegetation and the

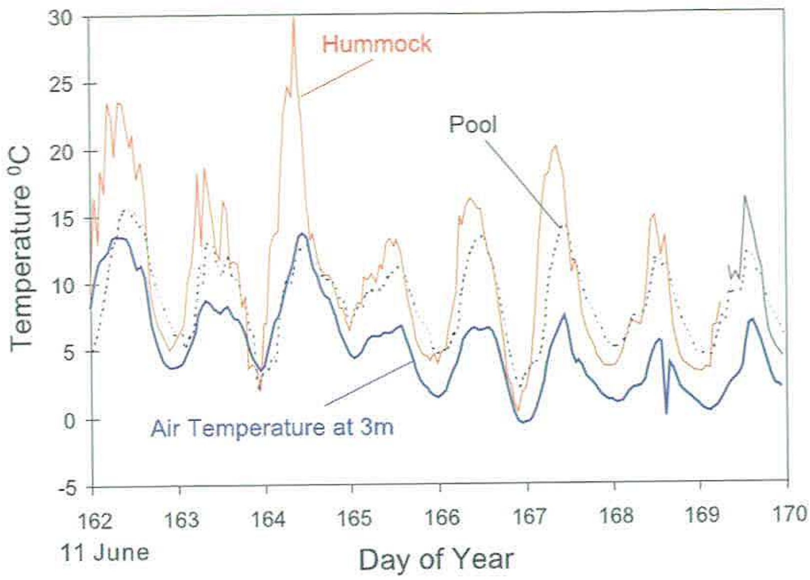


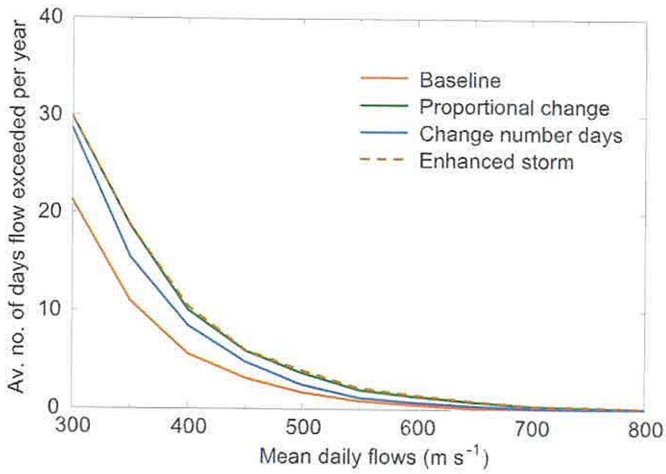
Figure 26. The air temperature and surface temperatures of adjacent hummock and pool at the Kevo mire site during an eight-day period in early June 1997

soil respiration. Although annual carbon switching has not been seen at the other sites, changes from sources to sinks do occur during the summer period in response to hydrological processes: annual carbon budgets are therefore highly variable.

Contact: Colin Lloyd

IMPACT OF CLIMATE CHANGE ON RIVER FLOODING IN THE UK

There have been many studies of the potential impacts on water resources and flow regimes of future climate change due to global warming. Most of these studies have concentrated on the changes in average flows: relatively few have looked at the impacts on the extreme ends of the flow regime. A semi-distributed rainfall-runoff model has been used here to simulate flow duration and flood frequency curves for the Severn catchment for the 2050s.



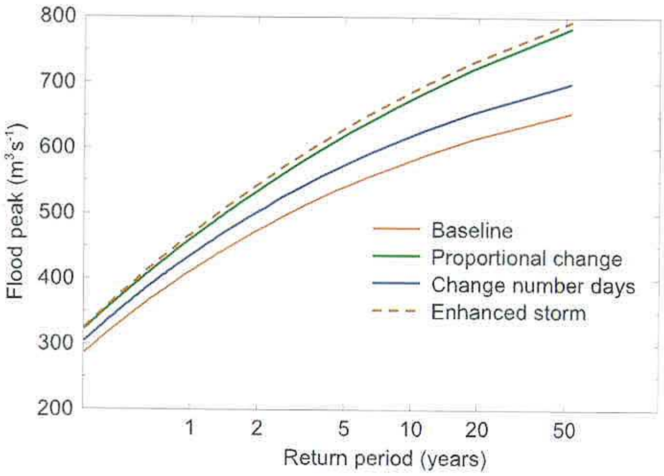


Figure 27. Flow duration and flood frequency curves for the Severn catchment under the three methods for applying the rainfall scenario

Figure 28. Disastrous flooding in Evesham on Good Friday, 1998 (Photo: © *Journal & Admag Series, Evesham*)

The model is based on a 40-km grid and has three components: a soil water balance model, a drainage model and a basin-wide routing model. The potential impacts of climate change were simulated by altering the driving climate variables and re-running the model for a 30-year period, representative of the middle of the next century. The climate change scenarios were constructed using the output from the most recent Hadley Centre general circulation model experiments (HadCM2).

The scenarios of change in average monthly rainfall for the 2050s have been applied in several ways. First, the monthly rainfall was perturbed by changing the rainfall on each wet day by the same percentage. The second approach was to alter the number of rain days in each month, increasing their number during the winter and decreasing it during the summer. The final method is to change only those rain days with rainfall above a certain threshold, thereby enhancing the storm profiles.

The curves in Figure 27 show that both the magnitude and frequency of flooding events in the Severn increase in the 2050s. The red line represents the current situation; the green line shows the response to a change in the mean monthly rainfall. The alternative rainfall scenarios cause the curves to shift upwards, but altering the number of days has less impact than either applying proportional changes or enhancing the storms. The impact of these scenarios is that the current 50-year flood, measuring about 650 $m^3 s^{-1}$, could increase to nearly 800 $m^3 s^{-1}$ by the middle of the next century, and the 650 $m^3 s^{-1}$ flow will no longer be exceeded, on average, once every 50 years, but every 10.

Contact: Nick Reynard

There is no diminution in the pace of IT developments: these can assist our scientific aims and our ability to make the outcomes available to interested bodies or the lay public. The first electronic Hydrological Yearbook UK (for 1996) available on the World Wide Web is at http://www.nwl.ac.uk/~nrfadata/yearbook/web/yb96/yearbook96.htm — this has made possible a larger set of processed data than could be achieved by hard copy production. The most frequently searched of the Institute's many web pages (for which the "hit" rate is 25 000 per month in total) is Waterwatch, a shortened version of our subscription bulletin, the Monthly Hydrological Summary for Great Britain, which can be found at http://www.nwl.ac.uk/ih/www/research/bdroughtwatch.html.

Integrating generic science

INFORMATION AND COMMUNICATION TECHNOLOGY ACTIVITIES

The articles below show that our research into efficient, accurate and powerful spatial dataset viewing has led us into pioneering work with oceanographic colleagues within NERC to create common fields of search across inland, intertidal and coastal areas. We have been assisted by European consortia members to create for the European Environment Agency its first vector dataset of the continent's rivers. And we have laid the groundwork for a new era in lowland catchment experimentation by the continuous high resolution calibrated monitoring of the quality of a cluster of chalk streams in Berkshire. The success of the LOIS thematic programme of science showed the wisdom of the NERC Data Policy document in calling for each programme of that type to have a Data Plan. Such plans ensure that all involved with multi-consortia research have equal access to new data (after a limited time for the first author to publish their findings) and that added value from the quality-controlled data is achieved by archiving it in a catalogued form for successive researchers. A consequence for our data management research team is that it has sought generic data models and common data dictionaries so that it can economically provide a range of Thematic Programmes with an effective Data Centre. This has been done with Environmental Diagnostics, and has included a distributed data centre approach with the involvement of the Environmental Change Research Centre at University College London. We also assisted the British Geological Survey with a Data Scoping Study for the URGENT programme, and secured (with Science Systems Ltd) British National Space Centre funds for innovative handling of satellite imagery of rivers.

The Library, which will have the necessary space for justified expansion as a consequence of the building contract commencing on the Wallingford site in autumn 1998, has implemented and loaded the UNICORN holdings management software, which is common to the whole of CEH. This is improving the pace at which scientific literature of importance to hydrology can be registered and located.

The Institute has taken advantage of the rapid strides made by the British library project "Internet Library of Early Journals" — http:/ www.bodley.ox.ac.uk/ilej/ — because of the environmental history data that it contains. A range of key 18th and 19th century series, including the Philosophical Transactions of the Royal Society, can now be searched rigorously by a few keystrokes — once the user is familiar with the subject being sought! An example of the strength of this approach can be seen in the assistance given by the Institute to the British Hydrological Society in order that it could launch a long-term project to create a chronology of hydrological events for Britain.

This went live on the Internet at the BHS International Conference on *Hydrology in a Changing Environment*, held at Exeter University in July 1998. Current progress can be seen at http:// www.dundee.ac.uk/geography/cbhe/. Its relevance has been highlighted by the increased interest in forming local flood chronologies since the severe Easter 1998 floods in the Midlands, but its science potential for the coming generation goes far wider than that.

Contact: Frank Law

EUROPEAN RIVERS AND CATCHMENTS (ERICA)

For hundreds of years hydrology has relied on high-quality time series datasets with which to test hypotheses and to help manage resources. As time has passed, many of these datasets have been transferred to an electronic medium and, more and more, modern capture is done directly to disk. This allows us to utilise ever-increasing computational power fully. But how useful is this if we cannot describe digitally the spatial relationships between these data and the environment from which they were captured?

In Britain, we have a high-resolution digital database of rivers and a hydrologically appropriate digital terrain model. At a European scale, each state has similar holdings, but there is no standardised and integrated dataset of rivers, lakes and catchment boundaries. This is a problem for a body such as the European Environment Agency (EEA), but one which they have solved by commissioning IH to provide a

"Low-resolution catchment geographic database". This comprises rivers, canals, lakes, coastline and international borders that extend across to the Ural Mountains, plus the 1000 largest catchments in the 15 EU member states, all at 1:1M scale.

The respected cartographers Bartholomews supplied the base data, which were subjected to exhaustive quality control and enhancement procedures. To aid navigation and analysis, all rivers have consistent direction, i.e. they are stored in point order from downstream to upstream, and are node matched. Paths through lakes ensure total connectivity from any river's source to its exit into the sea or ocean. River names in the local language and English have been added to over 32 000 stretches. All lakes and lake islands are complete polygons, which allows both calculation of total lake areas and enhanced mapping using colour infill. The catchment boundaries have been automatically identified and derived using an IH-devised method (Sekulin, Bullock and Gustard, 1992).

All of the datasets are mutually compatible: rivers reach, and stop, at the coast whilst having nodes at all river and river/lake intersections. The coast has nodes at river/coast intersections. And, where rivers form international boundaries, the boundary is identical to the path of the river. Over 1500 catchments were eventually included to give as wide a coverage as possible.

Input from the European Topic Centre for Inland Waters ensured that ERICA-1M complies with the needs of the EEA. They concluded that ERICA-1M is "a great advance in terms of the provision of a tool for assessment and visualisation". Its potential for use is obviously wide and the EEA has been approached by a number of research groups. Permission has been granted for its use on the ARIDE project — Assessment of the Regional Impact of Drought in Europe — and this is expected to be the first of many.

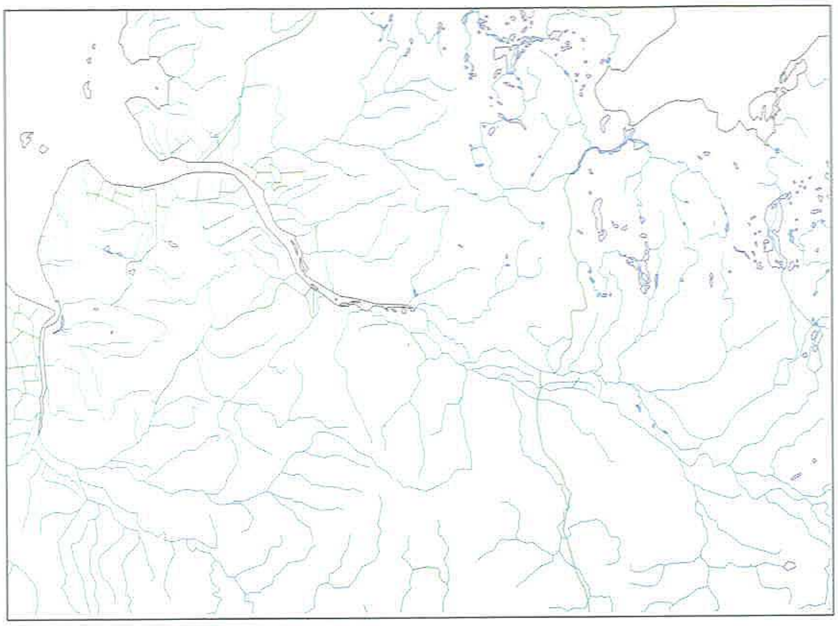


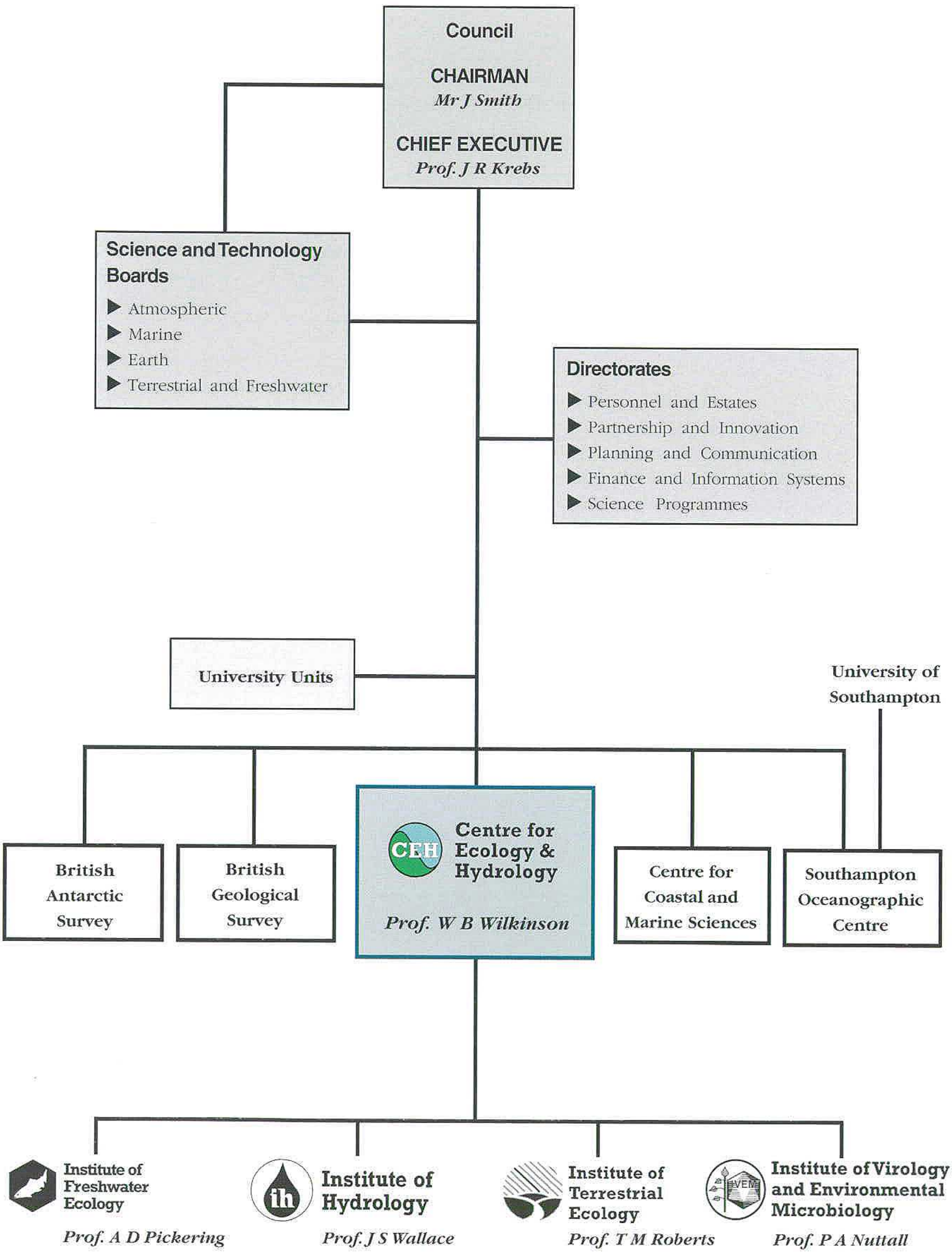
Figure 29. A sample of ERICA-1M displayed at 1:2M scale

In parallel to the low resolution study, the University of Freiburg and the National Environmental Research Institute of Denmark completed a pilot study at 1:250K. This concentrated on the Meuse in France and Belgium and the Miño in Spain and Portugal. Findings from this will help the EEA formulate plans to achieve the long-term goal of a pan-European medium resolution catchment geographic database.

Contact: Rob Flavin

APPENDIX 1

NERC structure



IH staff

Director
J S Wallace
R W Flavin (PA); *V Lynch* (PS)

Deputy Director
F M Law

Information & Scientific Services — ***F M Law***
- **Infrastructure** — *N R Runnalls*
- **National Water Archive** — *M L Lees*
- **Data & software systems** — *R V Moore*
- **Communications** — *C Kirby*
- **Library** — *S B Wharton*

Water Quality — ***A Jenkins***
- **Catchment water quality modelling** — *D B Boorman*
- **Hydrochemical processes** — *R J Williams*
- **Sediment interactions** — *P S Naden*
- **Experimental catchments** — *J A Hudson* (Wales)
- **Analytical chemistry** — *M Neal*
- **Thematic science management** — *G J L Leeks*

Bio-Physical Processes — ***J H C Gash***
- **Global processes** — *R J Harding*
- **Landscape interactions** — *M Robinson*
- **Water management & policy studies** — *C H Batchelor*
- **Vegetation & soil processes** — *J M Roberts*
- **Instrumentation** — *J D Cooper*

Risks & Resources — ***A Gustard***
- **Low flow, ecology & wetlands** — *M C Acreman*
- **Flood, rainfall & climate analysis** — *D W Reed*
- **Hydrological systems modelling** — *R J Moore*
- **Surface-groundwater systems** — *A F Calver*
- **Water resources** — *F A K Farquharson*

Administration Support — ***S M Pryde***
- **Finance & accounts** — *A S Dickerson*
- **Personnel & estate** — *W C Barnett*

Information & Scientific Services

Science remit

To provide the technology to ensure the Institute's science thrives and reaches its intended audience and users in the most appropriate format

Frank Law (Deputy Director & Division Head)
Sandie Butterfield (*Secretary*)

Roger Moore (Data & software systems)

Kevin Black – Software development
Richard Alexander
Lawrence Beran

Isabella Tindall – Software operations
Jeff Parker
Susan Renn

Martin Lees (National Water Archive)
Terry Marsh
Dave Morris
Samantha Green
Oliver Swain
Felicity Sanderson
Jackie Carr

Celia Kirby (Communications)
John Griffin
Rob Flavin

Sue Wharton (Library)
Pam Moorhouse

Chris Bottrell (Computing support)

Penny Kisby (IAHS Press)
Frances Watkins

Henry Gunston (DFID coordinator & IH Training Officer)

Neil Runnalls (Marketing & Business Development Manager)

Water Quality

Science remit

To understand the processes that control surface water quality and, by their representation within computer models, provide tools for improving water quality through environmental management

Alan Jenkins (Division Head)
Sue Beresford (*Secretary*)

David Boorman (Catchment water quality modelling)
David M Cooper
Andrew Eatherall
Rob Collins
Beate Gannon
Chris Evans
Andrea Marshall

Richard Williams (Hydro-chemical processes)
Colin Neal
Andrew Johnson
Atul Haria
Helen Jarvie
Craig White

Pam Naden (Sediment interactions)
Ian Littlewood
Carol Watts

Margaret Neal (Analytical chemistry)
Lal Bhardwaj
James Dodd
Martin Harrow
Linda Hill
Heather Wickham

Jim Hudson (Experimental catchments)
Phil Hill
Sue Hill
Alun Hughes

Graham Leeks (Thematic science management)
Howard Oliver
Ian Dwyer
Stephen Marks

Risks & Resources

Science remit

To provide advanced techniques for flood and low flow estimation, for forecasting extreme events, and for assessing the availability of water resources

Alan Gustard (Division Head)
Sandra Smith (*Secretary*)

Mike Acreman (Low flow, ecology & wetlands)
Gwyn Rees
Andy Young
Ann Sekulin
Gwyneth Cole
Karen Croker
David Hill
Mike Dunbar
Matt Holmes
Conor Linstead
Ian Gowing

Duncan Reed (Flood, rainfall & climate analysis)
David Marshall
Nick Reynard
Alice Robson
Lisa Stewart
Adrian Bayliss
Duncan Faulkner
Christel Prudhomme
Dorte Jakob

Bob Moore (Hydrological systems modelling)
David Jones
Vicky Bell
Enrico Frank

Ann Calver (Surface groundwater systems)
Dick Bradford
Sue Crooks
Rob Lamb
Helen Davies
Jana Crewett

Frank Farquharson (Water resources)
Jeremy Meigh
John Packman
Kevin Sene
Helen Houghton-Carr
Matthew McCartney
Val Bronsdon
Ned Hewitt
Emma Tate

Bio-physical Processes

Science remit

To improve quantiative understanding of the physical and biological processes in the terrestrial hydrological cycle, from local to global scales, including interaction with human activities

John Gash (Division Head)
Biddy Hawker (*Secretary*)

Charles Batchelor (Water management and policy studies)
Caroline Sullivan
Jeremy Cain

Richard Harding (Global processes)
Alistair Culf
Chris Huntingford
Colin Lloyd
Chris Taylor
Douglas Clark
Anne Verhoef

Mark Robinson (Landscape interactions)
Robin Hall
David Biggin
Eleanor Blyth
Ken Blyth
Jon Finch
Eleanor Burke

John Roberts (Transport mechanisms and water utilisation)
John Bromley
Chris Lovell
Ragab Ragab
Martin Hodnett
Mark Smith
Nick Jackson
Paul Rosier

J David Cooper (Instruments)
Andy Dixon
Dave McNeil
Sam Boyle
Jonathan Evans
Roger Wyatt
Mike Stroud
Geoff Wicks

Alan Warwick (Workshop)
Geoff Walley
John White

Administration

Stuart Pryde
(Head of Administration)

Bill Barnett (Personnel & Estate)

Ivor Standbridge *(Site Services)*
Denise Dolton
John Spencer
Harold Jones
Julie Butcher
Andy Sweetland *(Stores)*

Margaret Howarth *(Personnel & Office Services)*
Trish Sanders
Eileen Younghusband
Melanie Purvey
Anke Watson
Heather Turner
Jocelyn Cowley

Angela Rees *(Restaurant)*
Mary Wilkinson
Deborah Roberts

John Fraser *(Logistical Liaison Officer)*

Angie Dickerson (Head of Finance Group)

Sue Fenton *(Finance & Resource Management)*
Huw Thomas
Thelma Gibson
Lyn Ross

Anita Napper *(Accounts)*
Brenda Hall
Val Lambert

Further details on staff qualifications and job descriptions may be obtained from our WWW pages (see back cover).

APPENDIX 3

IH research programme

Soil and soil-vegetation interactions

Theme 1.1 Physico-chemical processes affecting soil-water interactions
Issue 1.1.1 Solid-solution partitioning of chemical species
Theme 1.3 Physical and physiological processes controlling soil water balances
Issue 1.3.1 Soil-root interactions at the individual plant root and stand scale
Issue 1.3.2 Soil-plant-atmosphere flux transfers in mixed vegetation
Issue 1.3.3 Root-soil-water interactions adjacent to fluctuating water tables

Land use science

Theme 2.2 Land use systems
Issue 2.2.3 Impacts of land use (change and management)
Issue 2.2.4 Development of land use and water resource management strategies
Theme 2.4 Landscape function and modelling
Issue 2.4.3 Integrated modelling of land use processes including social and economic variables

The urban environment

Theme 3.1 Factors and processes determing the development of urban environments
Issue 3.2.2 Urban impacts on hydrological processes
Issue 3.2.3 Aquatic ecosystem function
Theme 3.4 Urban water dynamics, risk and hazard
Issue 3.4.1 Low flows and pollution loads

Freshwater resources

Theme 4.1 Surface-groundwater interactions
Issue 4.1.1 The recharge-runoff division
Issue 4.1.2 The river-aquifer boundary and floodplain issues
Issue 4.1.3 Wetland interactions
Issue 4.1.4 Integrated catchment-scale analysis
Theme 4.2 Statistical modelling of resource availability
Issue 4.2.1 Estimation of resource availability at ungauged sites
Issue 4.2.2 Drought frequency estimation
Theme 4.3 Water resource modelling
Issue 4.3.1 Water resource management studies
Issue 4.3.2 Methodological developments
Issue 4.3.3 Risk analysis and decision support facility
Theme 4.4 Integrated water quality modelling
Issue 4.4.1 Monitoring and assessment
Issue 4.4.2 Understanding processes
Issue 4.4.3 Development and application of models
Theme 4.5 Integrated biotic response modelling
Issue 4.5.1 Flow resistance in channels and river ecosystems health
Issue 4.5.2 Integration of models of water quantity, quality and biotic variability

Biodiversity and population processes

Theme 5.1 Biodiversity characterisation, pattern and monitoring
Theme 5.4 Conservation and restoration of biodiversity
Issue 5.4.4 Wetland management and restoration

Pest and disease control

Theme 6.5 Distribution of pathogens in freshwater
Issue 6.5.1 Monitoring and risk assessment of pathogens in freshwater

Pollution

Theme 7.2 Acidifying pollutants
Issue 7.2.5 Surface water and catchment scale impacts
Issue 7.2.6 Modelling
Issue 7.2.7 Critical loads
Theme 7.4 Toxic metals
Issue 7.4.1 Transport and deposition
Theme 7.5 Organic pollutants
Issue 7.5.1 Monitoring
Issue 7.5.4 Physico-chemical processes controlling transport in soils and waters

Environmental risks and extreme events

Theme 8.1 Risk assessment and estimation of floods and other extreme events
Issue 8.1.1 Mainstream research
Issue 8.1.2 Generic solutions to 'joint probability' problem
Issue 8.1.3 Collective risk for environmental extremes
Issue 8.1.4 Continuous simulation modelling for flood estimation
Issue 8.1.5 Detection of trend and other nonstationary behaviour in time series of environmental extremes
Theme 8.2 Real-time flow and water quality forecasting and decision support systems
Issue 8.2.1 Methodological developments
Issue 8.2.2 Forecasting systems
Issue 8.2.3 Advances through special monitoring
Issue 8.2.4 Real-time water quality forecasting and decision support
Theme 8.3 Understanding and modelling the role of rare events on ecological systems
Issue 8.3.1 Rare events and ecological processes

Global change

Theme 9.1 Greenhouse gas budgets and cycles
Issue 9.1.2 Controls of net CO_2 and water/energy fluxes in Amazonia
Issue 9.4 Exchange mechanisms in high-latitude wetlands
Theme 9.2 Land-atmosphere-ocean interactions
Issue 9.2.1 Improved hydrological representations within GCMs
Issue 9.2.3 Snow-melt and routing models for northern latitudes
Issue 9.2.4 Dynamic ecosystem modelling
Theme 9.3 Forecasting and detecting the impacts of global change
Issue 9.3.1 Downscaling and predicting hydrological and water quality impacts

Integrating generic science

Theme 10.1 Environmental assessment, economics and history
Issue 10.1.1 Environmental valuation and quantitative prediction of environmental impacts
Theme 10.2 Remote sensing
Issue 10.2.2 Algorithms and models for estimation of biophysical variables
Issue 10.2.4 Generic data products from earth observation
Issue 10.2.5 Infrastructure and facilities
Theme 10.3 Instrumentation
Issue 10.3.1 Intelligent sensor clusters
Theme 10.6 Databases and reference collections
Issue 10.6.1 Integrity and accessibility of databases and collections within CEH
Theme 10.7 Biometrical applications, research and development
Issue 10.7.2 Application and development of biometrical methods

APPENDIX 4

Publications

1997
Refereed publications

Allen, S.J., **Roberts, J.M.**, **Smith, D.M.**, **Jackson, N.A.** and Lawson, G.J. 1997. Simulating the interaction between tree cover and crop temperature in integrated agroforestry models. *Agroforestry Forum* **8**, 20-23.

Andrews, A.J. 1997. The Southern African FRIEND database. In: Oberlin, G. (ed.), FRIEND Third Report: 1994-1997, CEMAGREF, France. 45-49

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Brilly, M. and **Gustard, A.** 1997. FRIEND '97 - Conference Proceedings, Regional Hydrology: Concepts and Models for Sustainable Water Resource Management. LOC Proceedings of oral presentations. *Acta Hydrotechnica* 15/18 (1997), Ljubljana.

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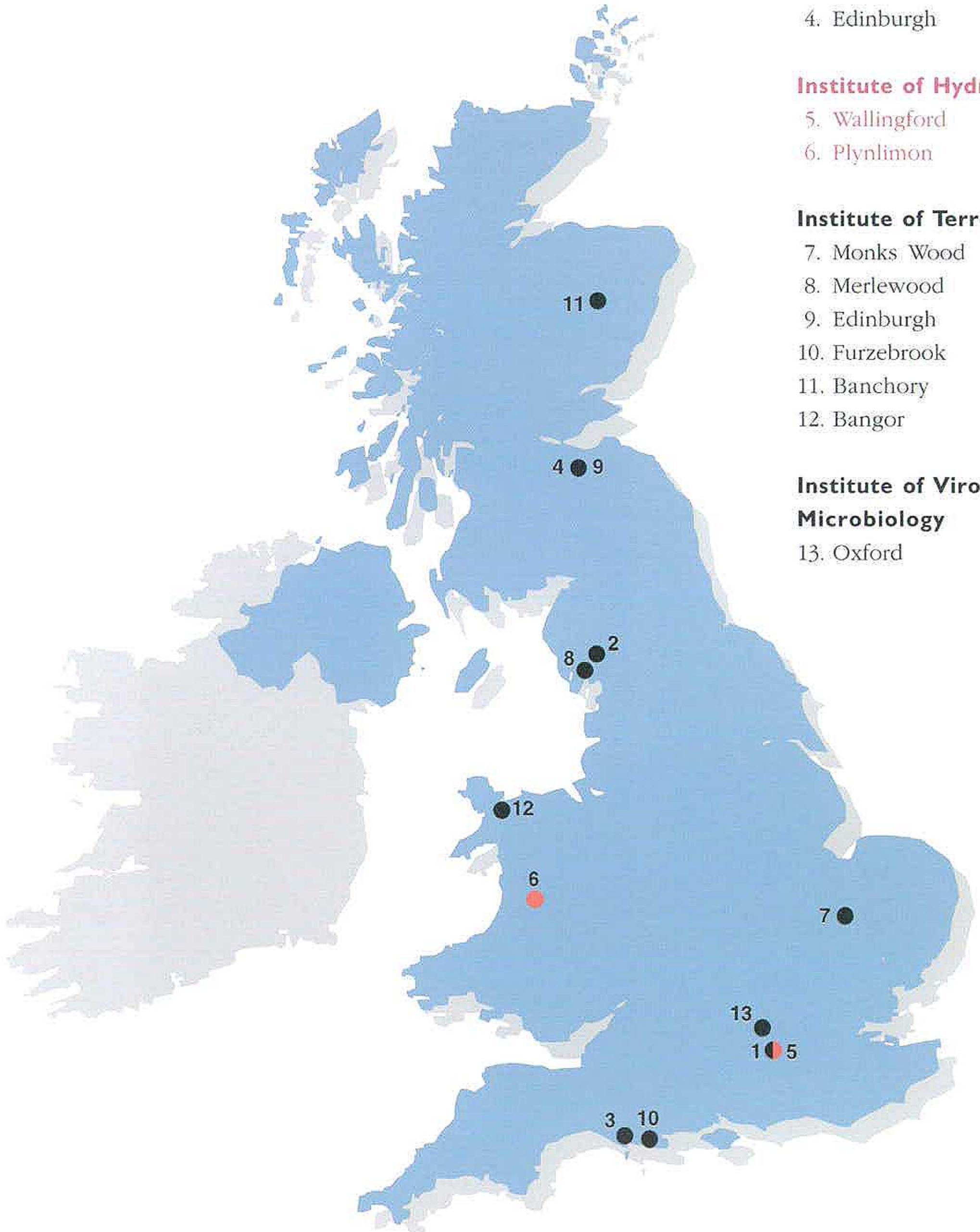
Location of CEH sites



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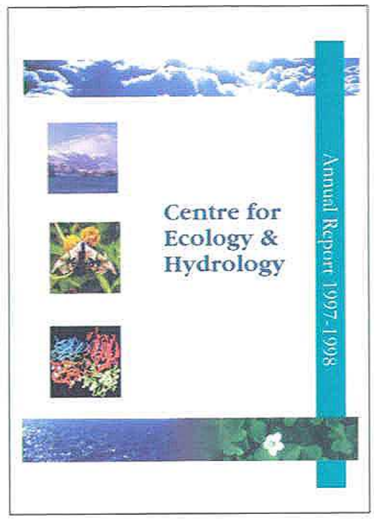

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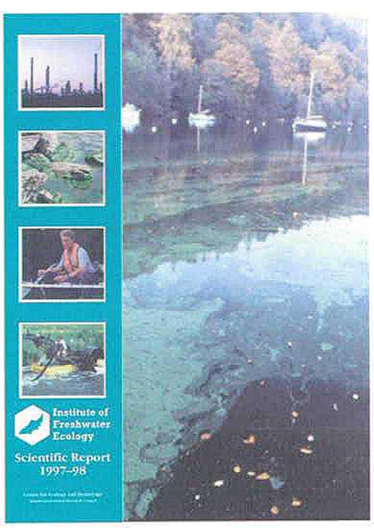

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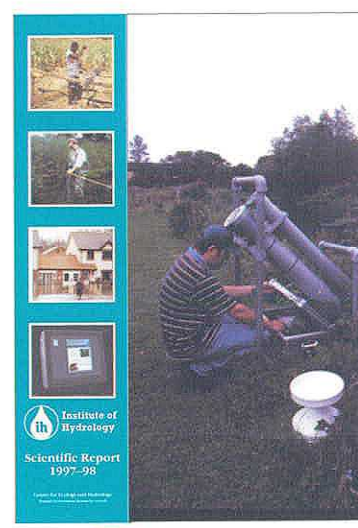

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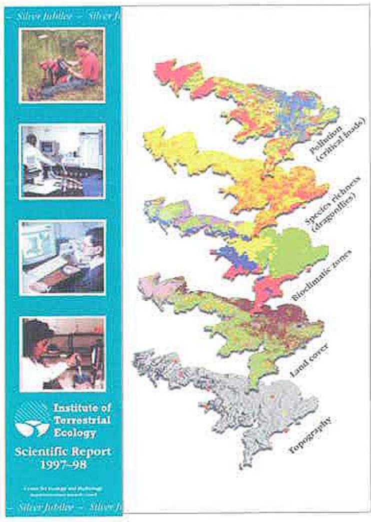

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